Signal impairment mitigation using mid-span spectral inversion (MSSI) and MSSI performance improvement using distributed raman amplification in WDM systems.

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Signal Impairment Mitigation using Mid-span Spectral Inversion (MSSI) and MSSI Performance Improvement using Distributed Raman Amplification in WDM Systems

Submitted to the University of Wales in fulfilment of the requirements for the Master Degree of Research (MRes), Photonic and Communication Systems.

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2010

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Abstract

In recent years, the ultra-long distance optical signal transmission and wavelength division multiplexing (WDM) systems play significant roles. However, even though there are a lot of techniques to compensate the signal impairment caused by fiber loss, group velocity dispersion and nonlinear effects, this problem is still not be completely solved. By noting the features of Mid-span spectral inversion (MSSI), this thesis examines compensation of the signal impairments caused by fiber loss, group velocity dispersion and nonlinear effects.

Firstly, this thesis theoretically proves that MSSI can compensate the impairments caused by dispersion and nonlinear effects by using nonlinear Schrodinger equation. In ideal case, the effects of even order dispersion and nonlinear effects in the first half link could be completely eliminated in the second half link after optical phase conjugation, which is the core technique in MSSI. However, the impairment caused by fiber loss and odd order dispersion cannot be compensated because of the lack of symmetry. Actually, higher odd order dispersion will have less effect on signal so we considered here only fiber loss. To solve this issue, the most effective method is to improve the symmetry of the loss gain cycle around the mid-point.

Raman amplification is considered to be used instead of EDFAs in this thesis because it is distributed amplification and will improve the loss/gain symmetry. As an example, a computer model is used to simulate a 4,000km WDM fiber link, with MSSI in the middle. The bit rate is 10Gbit/s and there are 6 channels. Both Raman amplification and EDFA are examined in this model. We have discovered that Raman amplification performs better than EDFA not only in low dispersion, low power situations but also in standard situation. In a standard fiber link (power= 1mW, β_2=-20ps^2/km), Raman amplification has a 3dB benefit than EDFA. And the penalty of Q value in Raman case is 1.9dB after 4,000km transmission in the absence of amplifier noise. That means by combining MSSI and Raman amplification, the impairment caused by fiber loss, group velocity dispersion and nonlinear effects can be compensated in WDM systems.

Contents

1. Introduction

The development of low-loss fiber (silica fibers, loss=0.2dB/km at 1, 550nm) has enabled the development of optical communication systems. At the same time, optical amplifiers permit propagation of lightwave signals over thousands of kilometers as they can compensate for all losses encountered by the signal in the optical domain. In addition, optical amplifiers enable the use of wavelength division multiplexing (WDM), which has led to the development of lightwave systems with capacities exceeding 1 Tb/s. However, the impairment cased by multiple reasons, such as dispersion, nonlinear effects and polarization, remains important problems which ultimately determined the system performance. [1][2][3]

1.1 Motivation of This Project

To compensate the signal impairment cased by dispersion, nonlinear effects and polarization, multiple techniques have been considered and applied in transmission, such as dispersion compensating fiber(DCF) and regenerator. However, considering the availabilities and cost, some other methods are always under investigation. [4]

Based on the background which is showed previously, we are going to study a novel technique named mid-span spectral inversion (MSSI) [5], which could reduce the impairments (increase in error rate or reduction in Q) caused by group velocity dispersion, nonlinear effects.[6]

There is another term named optical phase conjugation (PC), which is the core technique to achieve mid-span spectral inversion. Optical phase conjugation is very significant so it will be introduced later to explain mid-span spectral inversion.

1.2 Objectives of This Project

In this project, a system with 4,000 kilometers fiber will be simulated by a computer model based on the GNLS. The main objective of this project is to compensate the attenuation caused by group velocity dispersion and nonlinear effects. Mid-span spectral inversion will be the core technique to achieve this goal. Other methods may be applied if necessary. The simulation will start from a special case which has low dispersion (less than 2.0ps^2/km) and low power (peak power of launched soliton). Then it will adjust several parameters and finally get a model of fiber which has standard dispersion (-20ps^2/km) and standard launched power (1mW). In this model, amplifier noise is not included to achieve more approximate results.

The key objective of this project is to investigate the role of Raman amplification in a MSSI system with the idea of increasing the symmetry over discrete EDFAs. The penalty of Q value of both Raman amplifiers and EDFAs will be used to evaluate the performance of these two amplifications. Firstly, the research of Raman amplifiers and EDFAs will be processed respectively. Then the results will be combined to compare with. As above, the comparison will start from the case of low dispersion (less than -2ps^2/km) and low power (the peak power of launched solition). Then it will increase the dispersion to standard situation (-20ps^2/km) and finally increase the power to standard situation (1mW). The results presented in this thesis show that the use of Raman amplifiers can lead to substantially improved performance over that obtained with EDFAs.

1.3 Structure of This Thesis

The thesis begins following this chapter, which contains background knowledge, such as mid-span spectral inversion, optical phase conjugation, Raman amplifier, soliton, relevant to the simulation work described in the following chapters.

The content of Chapter 3 describes the results of the simulation in wavelength division mulplexing systems with mid-span spectral inversion technique. This is the main chapter which contains all the work I did and leads to the conclusion.

Chapter 4 is the conclusion, which summarizes this thesis and gives the conclusions of the research. Furthermore, in chapter 4 it also lists the limitations of this thesis and gives some idea that could be verified in future work.

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2. Background

This chapter contains the background knowledge that is relevant to the experimental work in this thesis.

Firstly, section 2.1 describes the mid-span spectral inversion, which is the method used in this thesis to reduce the impairments caused by group velocity dispersion and nonlinear effects. In this section, the definition and principle of mid-span spectral inversion will be introduced first, and then we are going to explain how mid-span spectral inversion compensates the key impairments.

Section 2.2 provides a background on Raman Amplifier, starting with a brief theoretical description including the effect of Stimulated Raman Scattering. All the demonstrated Raman Amplifier in this thesis relies on this effect. Furthermore, a comparison of Raman Amplifiers and Erbium-doped fiber amplifiers is described, which explains the reason we choose Raman Amplifier in this thesis.

Section 2.3 describes the nonlinear effects in optical fiber transmission, which is the most important issue to be dealt with in this thesis. Section 2.3.1 will introduce the nonlinear Schrodinger equation which is the key description of nonlinear effects in optical fiber transmission. Furthermore, we will prove how to use mid-span spectral inversion to reduce nonlinear effects. Section 2.3.2 describes the nonlinear effects caused by the refractive index of nonlinear optical media, in particular self phase modulation.

Section 2.4 provides a background on soliton, which is very important since it is the signal launched from transmitter. Based on the solitons' properties which are going to be introduced in the following section, they are not only of fundamental interest but also they have found practical applications in the field of fiber-optic communications [1].

2.1 Mid-span Spectral Inversion [1][2][3][4][5][6][7][8]

2.1.1 Definition

Mid-span spectral inversion is to use a device named optical phase conjugation in the middle of the link to invert the spectrum (See Figure 2.1). That presents a symmetrical distribution of both dispersion and nonlinear effects so the impairment caused by nonlinear effects and even order dispersion could be recovered theoretically. That is because the impairment produced on a pulse could be compensated by that produced on its conjugated phase, which is the exactly copy of the original pulse spectrally-inverted and with an opposite value of accumulated dispersion. The principle will be introduced in the following section. This term has a long history, which was first proposed in 1979 [2] and first demonstrated in 1993 [3]. The structure indicates that it can achieve long distance transmission with only a single compensating element.

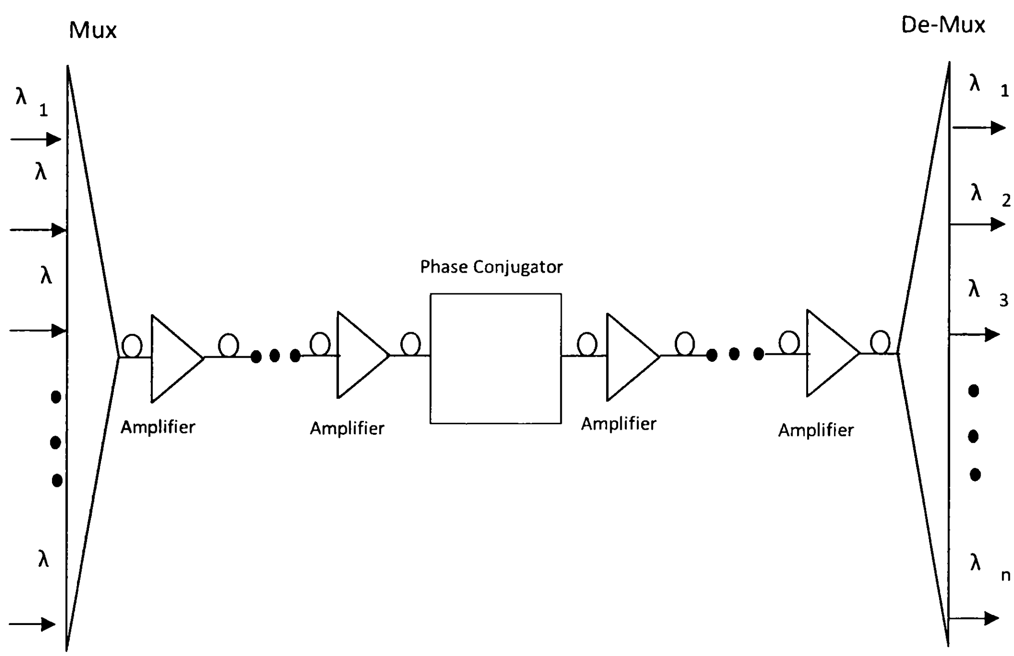


Figure 2.1 Schematic of dispersion management through mid-span phase conjugation in wavelength division multiplexing systems

Optical phase conjugation (OPC) is a laser-based technique developed since 1970s. Since it is feasible in many important applications, the research of OPC has become one of the most active research subjects in nonlinear optics.

Before the 1960s when the lasers were not practically invented [4], there were two impossibilities in the conventional optics. One was that there was no method (including any optical imaging systems or specially designed devices) could increase the brightness of any given light beam. This was solved by the invention of laser oscillators and amplifiers. The other was that the aberration influence from optical elements and propagating media made that a perfectly reversible optical system was impossible. This could be solved by OPC technique. [5]

Generally, a pair of optical waves is phase conjugated to each other by conjugating their complex amplitude functions with respect to their phase factors. Optical phase-conjugate waves can be generated through many nonlinear optical processes (such as four-wave mixing, three-wave mixing).

When the spectrum is inversed in the mid-point of transmission system, the signal impairment caused by group velocity dispersion and nonlinear effects before the mid-point will be compensated after the mid-point. Theoretically, the spectrum will be restored at the receiver in ideal case.

2.1.2 Principle of Operation

A typical plane-wave is defined as $\vec{A}(t,z) = A(z)\exp(-iwt)$. Then we are going to study how mid-span spectral inversion compensates the impairment caused by dispersion and nonlinear effects. The nonlinear Schrodinger Equation without loss section is [2]

$$\frac{\partial A}{\partial z} + \frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2} = i\beta_{NL} A \qquad [2.1].$$

where β_2 is defined as the second-order dispersion parameter. The nonlinear part is given by $\beta_{NL} = \delta_{nNL}\frac{\omega_0}{c}$. For optical fiber, the nonlinear change in the refractive index has the form $\delta_{nNL} = n_2 I$ and by definition, $I = \dfrac{P}{A_{eff}}$ where A_{eff} is the effective core area of the fiber. With $P = |A|^2$ and $\omega_0 = \dfrac{2\pi c}{\lambda_0}$ where λ_0 is the carrier wavelength, we obtain $\beta_{NL} = \gamma |A|^2, \gamma = \dfrac{2\pi n_2}{\lambda_0 A_{eff}}$ where the parameter γ takes into account various nonlinear effects occurring within the fiber. Then equation [2.1] could be transformed to

$$\frac{\partial A}{\partial z} + \frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2} = i\gamma |A|^2 A \qquad [2.2]$$

Now we shall explain how MSSI compensate for the dispersion and nonlinear effects. Transfer A to A^*, equation [2.2] will be transformed as

$$\frac{\partial A^*}{\partial z} + \frac{i\beta_2}{2}\frac{\partial^2 A^*}{\partial t^2} = i\gamma |A|^2 A^* \qquad [2.3]$$

Take the complex conjugate of equation [2.3], we have

$$\frac{\partial A}{\partial z} - \frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2} = -i\gamma |A|^2 A \qquad [2.4]$$

Transfer –z to z, the ∂z is $-\partial z$ now. Then equation [2.2] could be transformed as

$$-\frac{\partial A}{\partial z} + \frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2} = i\gamma |A|^2 A \qquad [2.5]$$

Times -1 on both sides of equation [2.5], we have

$$\frac{\partial A}{\partial z} - \frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2} = -i\gamma |A|^2 A \qquad [2.6]$$

Equation [2.6] is exactly equal to equation [2.4]. That means by taking the complex conjugate and reverse the propagation direction, the impairment caused by nonlinear effects and even order dispersion before MSSI could be recovered after MSSI.

However, the nonlinear Schrodinger Equation [2.2] only has nonlinear part and even order part. Then we are going to study whether MSSI could reduce the impairment caused by loss and odd order dispersion.

The nonlinear Schrodinger Equation included loss and odd order dispersion could be written as

$$\frac{\partial A}{\partial z}+\frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2}-\frac{\beta_3}{6}\frac{\partial^3 A}{\partial t^3}=i\gamma\,|A|^2\,A-\frac{\alpha}{2}A \qquad [2.7]$$

Transfer A to A^*, equation [2.7] will be transformed as

$$\frac{\partial A^*}{\partial z}+\frac{i\beta_2}{2}\frac{\partial^2 A^*}{\partial t^2}-\frac{\beta_3}{6}\frac{\partial^3 A^*}{\partial t^3}=i\gamma\,|A|^2\,A^*-\frac{\alpha}{2}A^* \qquad [2.8]$$

Take the complex conjugate of equation [2.8], we have

$$\frac{\partial A}{\partial z}-\frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2}-\frac{\beta_3}{6}\frac{\partial^3 A}{\partial t^3}=-i\gamma\,|A|^2\,A-\frac{\alpha}{2}A \qquad [2.9]$$

Use –z instead of z, the ∂z is $-\partial z$ now. Then equation [2.7] could be transformed as

$$-\frac{\partial A}{\partial z}+\frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2}-\frac{\beta_3}{6}\frac{\partial^3 A}{\partial t^3}=i\gamma\,|A|^2\,A-\frac{\alpha}{2}A \qquad [2.10]$$

Times -1 on both sides of equation [2.10], we have

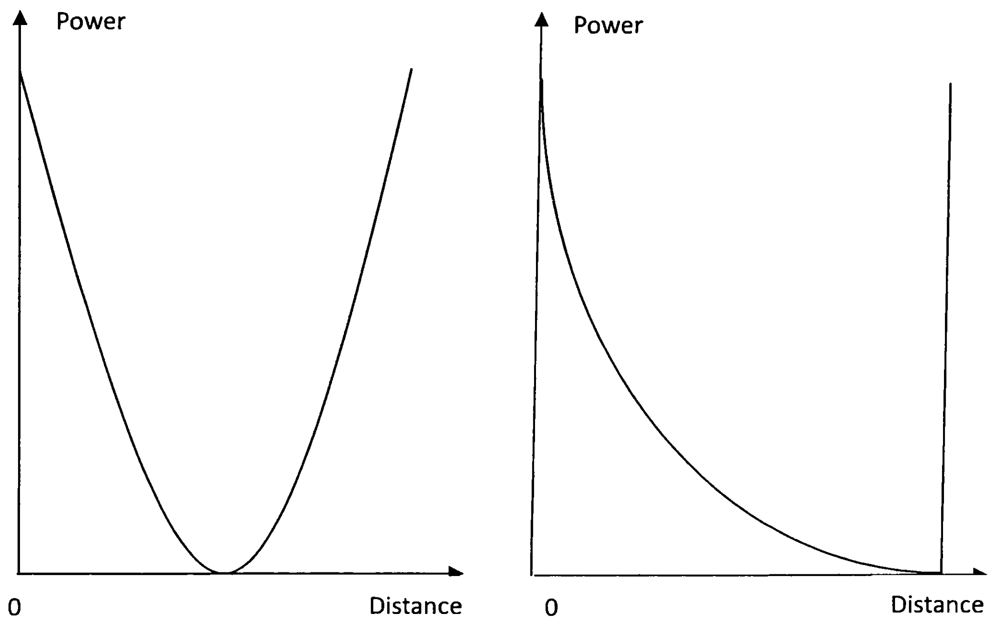
$$\frac{\partial A}{\partial z}-\frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2}+\frac{\beta_3}{6}\frac{\partial^3 A}{\partial t^3}=-i\gamma\,|A|^2\,A+\frac{\alpha}{2}A \qquad [2.11]$$

By comparing equation [2.9] and [2.11], we find that even though the even order dispersion and nonlinear parts are identical, the odd order dispersion and loss parts are not the same. That means the MSSI cannot recover the impairment caused by loss and odd order dispersion. The odd order dispersion is not the most important problem since the high order dispersion will have less effect on transmission systems. Therefore we are going to focus on the loss.

2.1.3 Issues

Even though mid-span spectral inversion can restore the distortion in ideal case such as no noise, it is impossible to create an absolutely ideal condition in practical work. There will be some issues we need to deal with and one of the most important is lack of symmetry in power caused by loss and amplifier gain.

Previously we introduced how mid-span spectral inversion undo the distortions caused by β_2 and γ. One condition to ensure that the spectrum will be restored at the receiver perfectly is the power should be symmetrical (see figure 2.2a). Otherwise, even though the spectrum could be restored, the percentage will not be 100%.



(a) (b)

Figure 2.2 Spectrum symmetry. (a) is the ideal symmetrical spectrum. (b) is the unsymmetrical spectrum in practical situation (EDFA).

However, because the attenuation caused by loss which cannot be compensated by mid-span spectral inversion is compensated by optical amplifiers, the spectrum will not be symmetrical (see figure 2.2b). Therefore, the lack of symmetry will be the biggest issue we need to deal with to obtain a better performance.

Considering the lack of symmetry is mainly caused by the loss, one idea is to select the suitable optical amplifiers to reduce the lack of symmetry. In this thesis, we assume that Raman amplifiers perform better than EDFAs because Raman amplification is distribution amplification which makes the symmetry better. We are going to study both Raman amplifiers and EDFAs in Chapter3 in a simple model set by computer and compare the results to prove the assumption.

There is another thing we need to notice. In equation [2.6], polarization is not included also. This should be considered in any future extension of this work.

2.2 Raman Amplifier [1][9][10][11][12][13][14][15]

Raman amplifiers are one kind of optical fiber amplifier which is based on Stimulated Raman Scattering. To compensate the attenuation caused by loss, previously Erbium-doped fiber amplifiers (EDFAs) are almost used commonly to amplify the signal transmitted in optical fibers to get ideal signals from receivers. Even though EDFAs became the most important amplification method in optical fiber transmission, there are still some issues they cannot deal with. In this situation, some other optical amplifiers are being considered, such as Raman Amplifier, which is based on Stimulated Raman Scattering.

2.2.1 Principle of Stimulated Raman Scattering (SRS)

In any molecular medium, spontaneous Raman scattering can transfer small power(about $\sim 10^{-6}$) from one optical field to another, whose frequency is downshifted by an amount determined by the vibration modes of the medium. This process was discovered by Raman in 1928 and is named as Raman Effect. The quantum mechanical description of Raman effect is that a photon of energy $\hbar\omega_p$ scattered by a molecule to a lower-frequency photon with energy $\hbar\omega_s$, as the molecule makes transition to a vibrational state. From a practical perspective, incident light acts as a pump and generates the frequency-shifted radiation, the so-called Stokes wave. It was observed that, for intense pump fields, the nonlinear phenomenon of SRS can occur in which the Stokes wave grows rapidly inside the medium such that most of the pump energy is transferred to it [1].

2.2.2 Raman Gain Spectrum

In a simple approach valid under the continuous wave and quasi-continuous wave conditions, the initial growth of the Stokes wave is described by [9]

$$\frac{dI_s}{dz} = g_R I_p I_s \qquad [2.12]$$

where I_s is the Stokes intensity, I_p is the pump intensity, and Raman gain coefficient g_R is related to the cross section of spontaneous Raman scattering [10].

The Raman gain coefficient $g_R(\Omega)$, where $\Omega \equiv \omega_p - \omega_s$ is the frequency difference between Stokes waves and the pump, is the most important element for describing SRS. Generally, g_R depends on composition of the fiber core and can dramatically change by using different materials. Moreover, it depends on whether Stokes waves and the pump are copolarized or orthogonally polarized. Figure 2.3 indicates g_R for fused silica as a function of the frequency shift [11]. The most important feature of the Raman gain in silica fibers is that $g_R(\Omega)$ extends over a large frequency range (up to 40THz) with a broad peak located near 13THz. As a result, it extends consecutively a broad range of frequencies in silica fibers to be compared with most molecular media for which Raman gain occurs at specific range of frequencies. This means that optical fibers can be used as broadband amplifiers by SRS. [1]

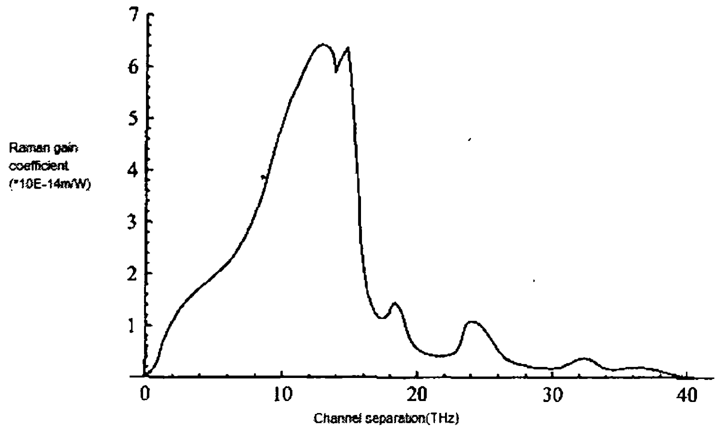


Figure 2.3 SRS gain coefficient as a function of channel separation.[1]

2.2.3 Raman Amplifiers

If the frequency difference of a weak signal and a strong pump wave which is launched together with the weak signal is within the bandwidth of the Raman gain spectrum, optical fibers can be used too as amplifiers. This kind of amplifiers is called Raman amplifiers, because this process is due to SRS. They have been made since 1976 and studied during the 1980s [1], and the development matured after 2000 when it is used in fiber-optic communication systems.

Consider the simplest situation in which a single continuous wave pump beam is launched. Equation [2.12] should be modified to add fiber losses before it can be used. Moreover, the pump power is not constant along the fiber, and the nonlinear interaction between the pump and Stokes waves must be considered. Therefore, the SRS process is represented by the following two coupled equations:

$$\frac{dI_s}{dz} = g_R I_p I_s - \alpha_s I_s \qquad [2.13]$$

$$\frac{dI_s}{dz} = -\frac{\omega_p}{\omega_s} g_R I_p I_s - \alpha_p I_p \qquad [2.14]$$

where α_s and α_p are respectively fiber losses at the Stokes and pump frequencies.

The gain provided by Raman amplifiers can be obtained from equation [2.13] and [2.14]. the amplification factor is given by

$$G_A = \exp(g_R P_0 L_{eff} / A_{eff}) \qquad [2.15]$$

where $P_0 = I_0 A_{eff}$ is the pump power at the amplifier input and $L_{eff} = [1 - \exp(-\alpha_p L)] / \alpha_p$.

One of the most important feature is their broad bandwidth (about 5THz). It could amplify several channels simultaneously in WDM systems. Raman amplifiers could be used to extend the bandwidth of WDM systems in 1550 nm region. [12][13][14] EDFAs are usually used in the same wavelength region, with a bandwidth of 40 nm. However, for WDM systems, optical amplifiers capable which could provide gain over 70 to 80 nm wavelength range are required.

Another reason to choose Raman amplifiers is, in long distance WDM systems, distributed Raman amplification is used to compensate fiber loss. In this case, Raman amplification can bi-directionally pump a long spans (about 80 to 100 kilometres) transmission fiber. Therefore, the fiber loss can be compensated by this method. [1]This technology is more effective for soliton systems.[15] By using distributed Raman amplification, the curve of power in one span is show as Figure 2.4a. Compared with the curve of power in EDFA case (see Figure 2.4b), it is obviously Raman amplifiers can partly reduce the impairment caused by the lack of symmetry.

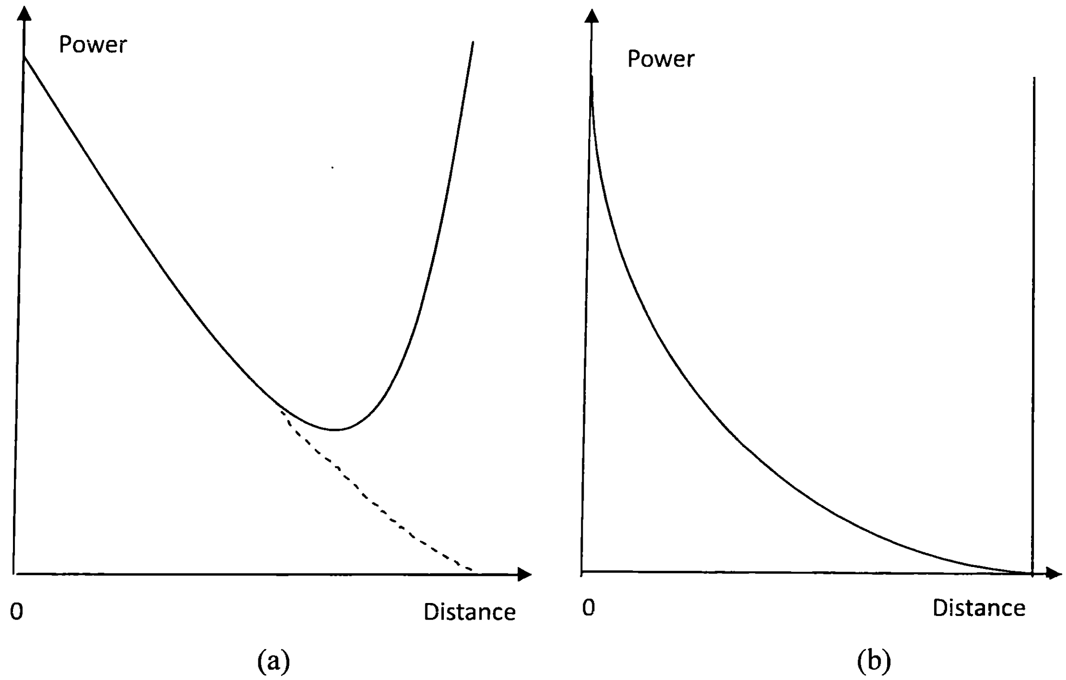


Figure 2.4 The power curves with different amplifiers in one span. (a) is the power of Raman amplifiers. The dashed line shows the power trend if there is no amplifier. (b) is the power for EDFA.

2.3 Soliton [1][11][16][17][18][19][20][21][22]

The term *soliton* refers to special kinds of wave packets that can propagate undistorted over long distance.[1] Solitons are narrow pulses with high peak powers and special shapes. Figure 2.5 shows the shape of a fundamental soliton pulse and its envelop. It was first observed by J. Scott. Russell in 1834 whilst riding on horse beside the narrow Union canal near Edinburgh, Scotland. The water wave caused by a boat kept the shape for a long distance even though the boat stopped. This phenomenon gave him some enlightenment so he did extensive experiments in a laboratory scale wave tank to research this phenomenon further. [16]

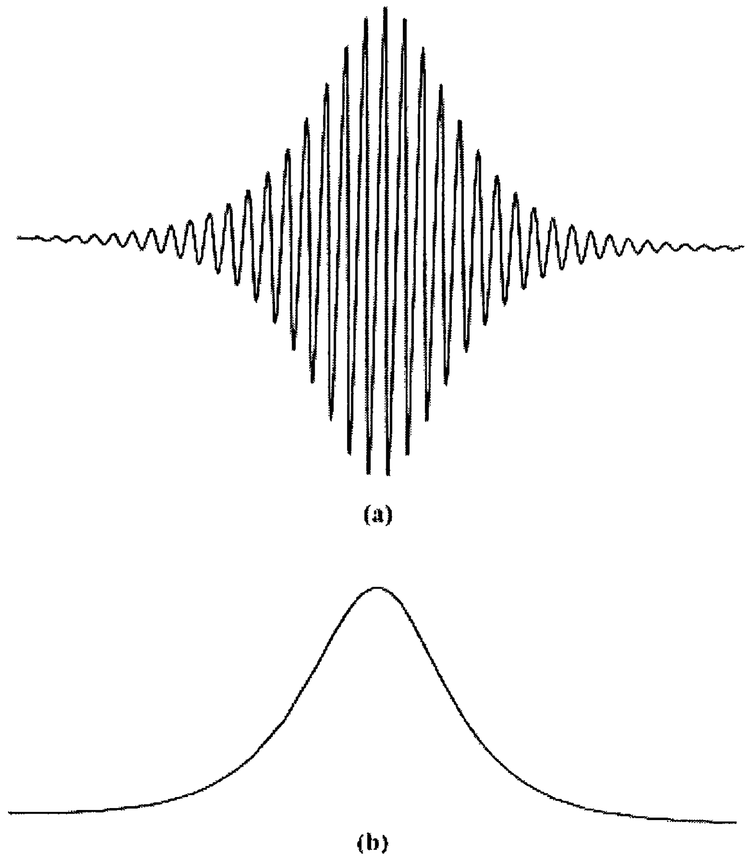


Figure 2.5 (a) A fundamental soliton pulse (b) the envelop of this soliton pulse.[after reference 11]

As most pulses undergo broading due to dispersion when propagating in optical fiber, the feature of soliton becomes very important in signal transmission. It is formed as a result of interplay between the dispersion and nonlinear effects [11]. This feature of soliton makes it very suitable for long distance transmission and that is the reason it is selected in this thesis.

To find out the solution of the nonlinear Schrodinger equation, the starting point is to simplify it. It takes the form

$$\frac{\partial A}{\partial z}+\frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2}=i\gamma\,|A|^2\,A \qquad [2.16]$$

if fiber loss is ignored. By introducing three dimensionless variables

$$U = \frac{A}{\sqrt{P_0}} \qquad \xi = \frac{z}{L_D} \qquad \tau = \frac{T}{T_0} \qquad [2.17]$$

Equation [2.16] can be transformed to

$$i\frac{\partial U}{\partial \xi} = \mathrm{sgn}(\beta_2)\frac{1}{2}\frac{\partial^2 U}{\partial \tau^2} - N^2 |U|^2 U \qquad [2.18]$$

where P_0 is the peak power (will be introduced in Chapter 3), T_0 is the width of the incident pulse, and the parameter N is introduced as

$$N^2 = \frac{L_D}{L_{NL}} \approx \frac{\gamma P_0 T_0^2}{|\beta_2|} \qquad [2.19]$$

The dispersion length L_D and the nonlinear length L_{NL} are defined as

$$L_D = \frac{T_0^2}{|\beta_2|} \qquad L_{NL} = \frac{1}{\gamma P_0} \qquad [2.20]$$

To eliminate the parameter N from equation [2.18], we introduce

$$u = NU = \sqrt{\gamma L_D} A \qquad [2.21]$$

Then equation [2.18] takes the standard form of NLS as

$$i\frac{\partial u}{\partial \xi} + \frac{1}{2}\frac{\partial^2 u}{\partial \tau^2} + |u|^2 u = 0 \qquad [2.22]$$

Where the choice sgn(β_2) =-1 has been made to keep focus on the case of anomalous group velocity dispersion. Based on the scaling relation in equation [2.22], if $u(\xi,\tau)$ is a solution of this equation, $\varepsilon u(\varepsilon^2\xi, \varepsilon\tau)$ is also a solution, where ε is an close up scaling factor.

In the inverse scattering method, the scattering problem associated with equation [2.22] is found to be [1]

$$i\frac{\partial v_1}{\partial \tau} + u v_2 = \xi v_1 \qquad [2.23]$$

$$i\frac{\partial v_2}{\partial \tau} + u^* v_1 = -\xi v_2 \qquad [2.24]$$

where v_1 and v_2 are the amplitudes of the two waves scattered by the potential

$u(\xi,\tau)$. ξ, the eigenvalue , plays a role similar to that played by the frequency in the standard Fourier analysis except that ξ can take complex values when u≠0. This feature can be identified by noticing that, it the part of potential is not included (u=0), v_1 and v_2 vary as $\exp(\pm i\xi\tau)$.

Equation [2.23] and [2.24] apply for all value of ξ. They are first solved at ξ=0 in the inverse scattering method. For a given initial form of u(0,τ), equation [2.23] and [2.24] are solved to obtain the initial scattering data. The direct scattering problem is described by a reflection coefficient r(ξ) which plays a part in analogous to the Fourier coefficient. The bound states (solitons) formation comes up to the poles of r(ξ) in the complex ξ plane. Therefore, the initial scattering data consist of the reflection coefficient r(ξ), the complex poles ξ_j, and their residues c_j, where j=1 to N if N such poles exist. Although the parameter N of equation [2.19] has not to be an integer, the same notation is used for the number of poles to stress that the number of poles is determined by its integer values.

Evolution of the scattering data along the fiber length is determined by using well-known techniques [17]. The solution $u(\xi,\tau)$ we desired is reproduced from the evolved scattering data using the inverse scattering method. This step is quite cumbersome mathematically since it requires the solution of a complicated linear integral equation. However, in specific case in which r(ξ) vanishes for the initial potential $u(0,\tau)$, the solution $u(\xi,\tau)$ can be figured out by solving a set of algebraic equations. This case corresponds to solitons. The soliton order is represented by the number N of poles, or eigenvalues ξ_j (j=1 to N). The general solution can be written as [18]

$$u(\xi,\tau) = -2\sum_{j=1}^{N}\lambda_j^{*}\Psi_{2j}^{*} \qquad [2.25]$$

Where

$$\lambda_j = \sqrt{c_j}\exp(i\xi_j\tau + i\xi_j\xi) \qquad [2.26]$$

and Ψ_{2j}^* is obtained by solving the following set of algebraic linear equations:

$$\Psi_{1j} + \sum_{k=1}^{N} \frac{\lambda_j \lambda_k^*}{\xi_j - \xi_k^*} \Psi^*_{2k} = 0 \qquad [2.27]$$

$$\Psi_{2j}^* - \sum_{k=1}^{N} \frac{\lambda_j^* \lambda_k}{\xi_j^* - \xi_k} \Psi_{1k} = \lambda_j^* \qquad [2.28]$$

Generally, the eigenvalues ξ_j are complex ($2\xi_j = \xi + i\eta_j$). Physically, the real part ξ_j produces a change in the group velocity relevant to the jth component of the soliton. For the To remain bound of the Nth order soliton, it is necessary that all of its components propagate at the same speed. Therefore, all eigenvalues ξ_j should lie on a line parallel to the imaginary axis, i.e., $\xi_j = \xi$ for all j. This feature simplifies the general solution in Equation [2.26]. It will be seen that the parameter ξ represents a frequency shift for the soliton from the carrier frequency ω_0.

The first order soliton (N=1) represents the case of a single eigenvalue. It is referred to as the fundamental soliton because the shape keeps the origin on propagation. Its field distribution is obtained from equation [2.25] to [2.28] after setting j=k=1. Notice that $\Psi_{21} = \lambda_1(1+|\lambda_1|^4/\eta^2)^{-1}$ and substitute it in equation [2.25], we obtain

$$u(\xi,\tau) = -2|\lambda^*{}_1|^2 (1+|\lambda_1|^4/\eta^2)^{-1} \qquad [2.29]$$

After using equation [2.26] for λ_1 together with $\xi_1 = (\delta + i\eta)/2$ and introducing the parameters τ_s and φ_s through $-c_1/\eta = \exp(\eta\tau_s - i\phi_s)$, we obtain the following general form of the fundamental soliton:

$$u(\xi,\tau) = \eta\, \mathrm{sec}\,h[\eta(\tau - \tau_s + \delta\xi)]\exp[i(\eta^2 - \xi^2)\xi/2 - i\delta\tau + i\phi_s] \qquad [2.30]$$

where η, δ, τ_s and φ_s are four arbitrary parameters that describe the soliton. Therefore, an optical fiber link supports four parameters of fundamental solitons, all at the condition N=1.

Physically, the four parameters η, δ, τ_s and φ_s respectively represent amplitude, frequency, position and phase of the soliton. The phase φ_s can be ignored from the discussion because a constant absolute phase has no physical significance. It will become relevant when nonlinear interaction between a pair of solitons is considered. The parameter τ_s can also be ignored since it points out the position of the soliton peak. In case the origin of time is chosen such that the peak occurs at τ=0 at ξ=0, one can set τ_s=0. Based on the phase factor in equation [2.30], it is clear that the parameter δ represents a frequency shift of the soliton from the carrier frequency ω_0. With the carrier part, exp(-i ω_0t) , the new frequency becomes $\omega'_0 = \omega_0 + \delta/T_0$. Notice that frequency shift also changes the transmission velocity of soliton from its original value v_g. This can be seen more clearly by introducing $\tau=(t-\beta_1 z)/T_0$ in equation [2.30] and writing it as

$$|u(\xi,\tau)| = \eta \sec h[\eta(t-\beta_1' z)/T_0] \qquad [2.31]$$

where $\beta_1' = \beta_1 + \delta|\beta_2|/T_0$. As expected, the group velocity ($v_g=1/\beta_1$) changes with a consequence of fiber dispersion.

The frequency shift δ can also be replaced from equation [2.30] by choosing the carrier frequency appropriately. Fundamental solitons then has single parameter which is described by

$$u(\xi,\tau) = \eta \sec h(\eta\tau)\exp(i\eta^2\xi/2) \qquad [2.32]$$

Not only the soliton amplitude but also its width is determined by the parameter η. In real units, the soliton width changes with η as T_0/η, i.e., it scales inversely with the soliton is the most crucial property of solitons. The canonical form of the fundamental soliton is achieved by choosing u(0,0)=1 so that η=1. With this choice, equation [2.32] can be transformed to

$$u(\xi,\tau) = \sec h(\tau)\exp(i\xi/2) \qquad [2.33]$$

Equation [2.33] can prove that the solution of equation [2.22] is a soliton and it is the pulse we launched by using sech function.

In this section, there is another important term: average soliton, which should be used for stable operation of a soliton communication system. For average soliton, the field is described as $E = u[\frac{2\Gamma z_a}{1-e^{-2\Gamma z_a}}]^{\frac{1}{2}}$,where u is the field of single soliton and $g = \Gamma z_a$ is the gain of amplifiers[21]. Based on this result, the launched power in this thesis for average soliton could be calculated. [1][11][19][20]

2.4 Summary

In this section, the background knowledge is introduced, such as mid-span spectral inversion, optical phase conjugation, Raman amplifier and soliton. Based on this knowledge, we are going to set up a model which can simulate the signal transmission on computer. That will prove our assumption and evaluate the system performance.

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3. Simulation and Results

In this chapter, the system performance of a WDM MSSI link as described in section 2.2 in wavelength division multiplexed (WDM) systems will be showed. In order to establish a simple model, a 6-channels model will be used and one of the central channels (the fourth channel) would be used as sample. All the results in this chapter are based on Channel 4. In this chapter, the system performance of Raman amplifier and EDFA will be studied first. Then the results of these two parts will be combined to figure out the relationship of them, and find out the advantages and disadvantages of them. In the end, these results will be used to established a model in standard fiber, which has 1mW launched power, -20ps^2/km dispersion. Amplifier noise is not included in this model.

The system performance is ideally measure in terms of bit error rate (BER) but this is beyond the calculation capability for numerical methods when the error rate is low. Here we shall calculate a term named Q value which relates directly to the BER. Bit error rate is one of the most common figures of merit to evaluate the system performance. It is defined as N_E , the number of bit errors occurring over a time interval, divided by N_T, the total number of bits sent during the same interval. In another word, BER= N_E/ N_T. By definition, bit error rate is expressed by a dimensionless number. Typically, bit error rate in optical signal transmission has a range from 10^{-9} to 10^{-15}. [1]

Figure 3.1 shows the probability density function (PDF) for the observed photocurrent for a typical receiver in an optical binary digital system. In figure 3.1, I_1 represents the mean of binary "1", I_0 represents the mean of binary "0", σ_1 represents the root square of variance of binary "1" and σ_0 represents the root square of variance of binary "0". The probability of error = P[0]P[1|0]+P[1]P[0|1], where P[0] represents the probability of a "0" was transmitted, P[1] represents the probability of a "1" was transmitted, P[1|0] represents the probability of a "1" was received given that a "0" was transmitted, P[0|1] represents the probability of a "0" was received given that a "1" was transmitted. Then we have [2]

$$P[1|0]=\frac{1}{\sigma_0\sqrt{2\pi}}\int_{I_D}^{+\infty}\exp\{\frac{(\langle I_0\rangle-I)^2}{2\sigma_0^2}\}dI \quad [3.1]$$

$$P[0|1]=\frac{1}{\sigma_1\sqrt{2\pi}}\int_{\infty}^{I_D}\exp\{\frac{(\langle I_1\rangle-I)^2}{2\sigma_1^2}\}dI \quad [3.2]$$

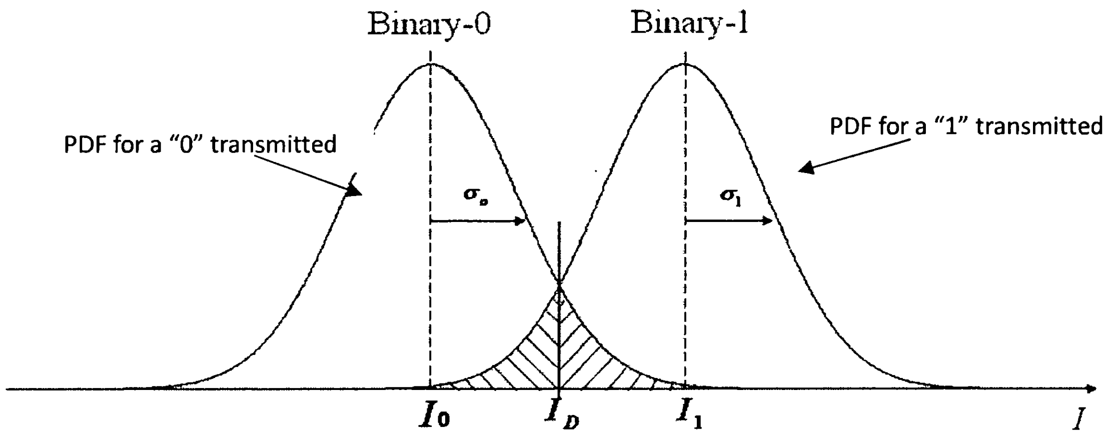


Figure 3.1 Probability density function (PDF) for the observed photocurrent for a typical receiver in an optical binary digital system. [after reference 3]

By combining equation [3.1] and equation [3.2], the bit error rate could be expressed as

$$BER=\frac{1}{\sqrt{2\pi}}\int_0^{\infty}\exp(-\frac{x^2}{2})dx\approx\frac{1}{\sqrt{2\pi}}\frac{e^{-\frac{Q^2}{2}}}{Q} \quad [3.3]$$

where Q represents the signal noise ratio (SNR). The Q is defined as

$$Q=\frac{I_1-I_0}{\sigma_1+\sigma_0} \quad [3.4]$$

Based on equation [3.3], when the Q value increases, the bit error rate decreases. Some common values are Q=6 for BER=10^{-9}, Q=7 for BER=10^{-12}, Q=8 for BER=10^{-15}. The higher the Q value is, the lower bit error rate the system has. In another word, big Q value indicates the system has a low impairment in signal transmission. [1]

Typically very low BER such as 10^{-9} or lower is required. However, the use of forward error correction (FEC) makes the requirement to be relaxed. The norm in recent years is to use a target BER of 10^{-3} when reporting research results. In fact, the ITU standard FEC is capable of operating with received BERs for up to 3×10^{-3}. [4]

To be compared with easily, the Q values have been converted to dB. The relationship between Q and Q in dB is

$$Q(dB) = 20 \times \log_{10} Q \qquad [3.5]$$

By equation [3.5], the common values are Q=15.6dB for BER=10^{-9}, Q=16.9dB for BER=10^{-12}, Q=18.1dB for BER=10^{-15}. In this thesis, the Q value at the receiver is not perfect to exam the system performance because several effects, such as amplifier noise which will affect the results, are not included. Therefore, the result we want to use to evaluate the system performance is the penalty of Q from the transmitters to the receivers. In this thesis the norm is set as 3dB, which means the maximum penalty of Q which can be accepted is 3dB.

Before we use Q value to evaluate the system, the eye diagram will be firstly used to evaluate the system as a whole. In telecommunication, an eye diagram, also known as an eye pattern, is an oscilloscope display in which a digital data signal from a receiver is repetitively sampled and applied to the vertical input, while the data rate is used to trigger the horizontal sweep. It is so called because, for several types of coding, the pattern looks like a series of eyes between a pair of rails. Figure 3.2 shows an example of an on-off key eye diagram.

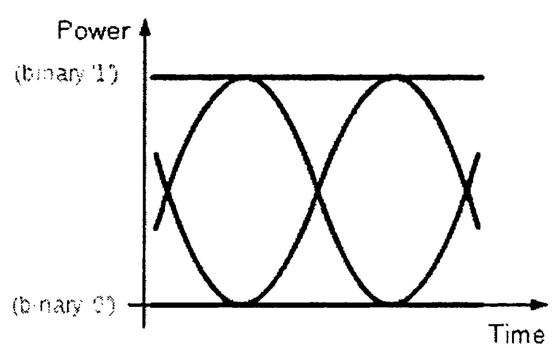


Figure 3.2 Graphical eye pattern showing an example of two power levels in an OOK modulation scheme. Constant binary 1 and 0 levels are shown, as well as transitions from 0 to 1, 1 to 0, 0 to 1 to 0, and 1 to 0 to 1.

Several system performance measures can be derived by analyzing the display. If the signals are too long, too short, poorly synchronized with the system clock, too high, too low, too noisy, too slow to change, or have too much undershoot or overshoot, this can be observed from the eye diagram. An open eye diagram corresponds to minimal signal distortion. Distortion of the signal waveform due to intersymbol interference and noise appears as closure of the eye pattern. [5][6]

There is three features usually used to measure the signal. They are eye opening (height, peak to peak), eye overshoot/undershoot and eye width, respectively represent additive noise in the signal, peak distortion due to interruptions in the signal path and timing synchronization and jitter effects. The eye diagrams shown below are printed directly by NLSViewer, which is a software on the computer.

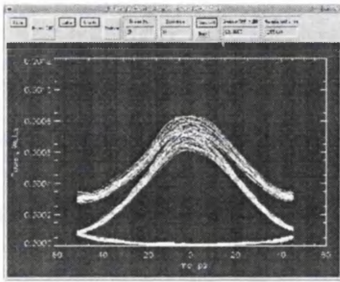
Section 3.1 shows the system performance with Raman amplifiers and mid-span spectral inversion. The launched power in this section is the peak power of the launched soliton. The peak power of the first order soliton is given by $P = \frac{|\beta_2|}{\gamma T_0^2} \approx \frac{3.11|\beta_2|}{\gamma T_{FWHM}^2}$ where the FWHM of the soliton is given by $T_{FWHM} \approx 1.76 T_0$ [7].

In this model it is given by $T_{FWHM} = 50ps$. β_2 is the dispersion parameter and γ takes into account various nonlinear effects occurring within the fiber. When $n_2=2.6\times10^{-20}m^2/W$, γ takes values in the range 1-10 $km^{-1}W^{-1}$. To be specific, if $\gamma=1$ $km^{-1}W^{-1}$ and $\beta_2=-1$ ps^2/km, P should be 1.244mW. The dispersion parameters β_2 are smaller than standard fiber. Section 3.2 indicates the same situation in Section 3.1, except using EDFAs instead of Raman amplifiers. Section 3.3 compares the results of Section 3.1 and Section 3.2, in order to find out optimum amplifier between Raman amplifiers and EDFAs. Section 3.4 keeps on comparing the performances of Raman amplifiers and EDFAs in a standard power (set the launched power as 1mW instead of the power of launched soliton) but also in a low dispersion (set $\beta_2=-1.2ps^2/km$). Section 3.5 will study the system performance on both Raman amplifiers and EDFAs in standard power (set the launched power as 1mW and the $\beta^2=-20ps^2/km$).

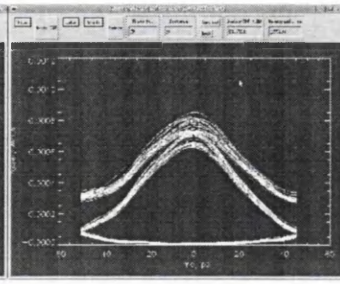
3.1 System performance with MSSI in WDM systems: Raman Amplifier

To use WDM systems in this model, we insert the code WDMify (-0.125, 0.05, 6, 0), which means the first frequency of this WDM system is -0.125THz before the central frequency (the wavelength is 1550nm and the central frequency is 195THz), the channel spacing is 0.05THz, the number of channel is 6 and the neighboring channel will not be orthogonally polarized. That means the link which has 50 spans of 80 kilometers is now be divided to 25 spans before MSSI and 25 spans after, with simple conjugations at the midpoint. Conjugate (), which is used to conjugate the optical phase in the fiber, is set up between them. In this case, fiber loss α=0.2dB/km and the Raman gain is 16dB to compensate the loss. The amplifier noise is not included. The transmission rate is 10Gb/s, in another word, the bit period is 100ps. The single pulse which has a 50ps pulse width (FWHM) is transformed into a 128-bitpattern and the pseudo random bit sequence (PRBS) [8][9] size is 7.

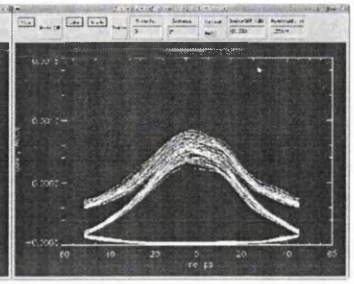
By checking the eye patterns and Q values of this model (see Figure 3.3), we found that the system performance is acceptable when the dispersion parameter $|\beta_2|$ is not larger than 1.6ps^2/km. However, when it is larger than 1.6ps^2/km, the eye diagram shows that there is distortion due to the dispersion and nonlinear effects in the signal and the eye opening height becomes lower. Based on these, the Q values must become worse and it will give a high bit error rate.



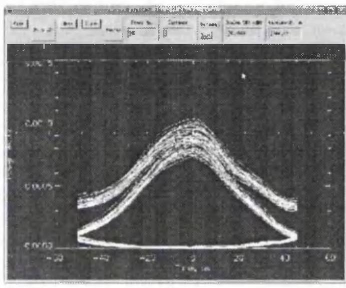
(a)



(b)



(c)



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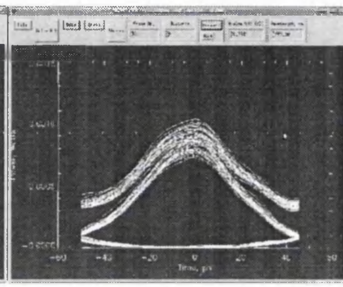

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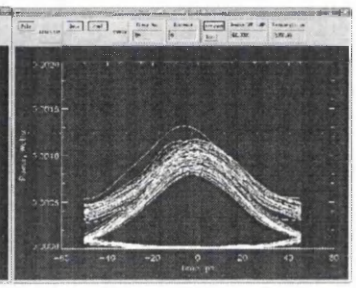
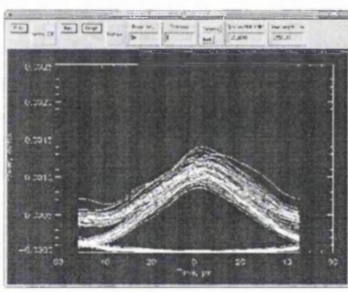
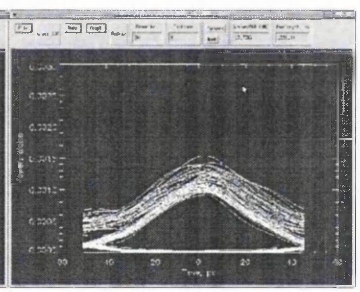


(f)

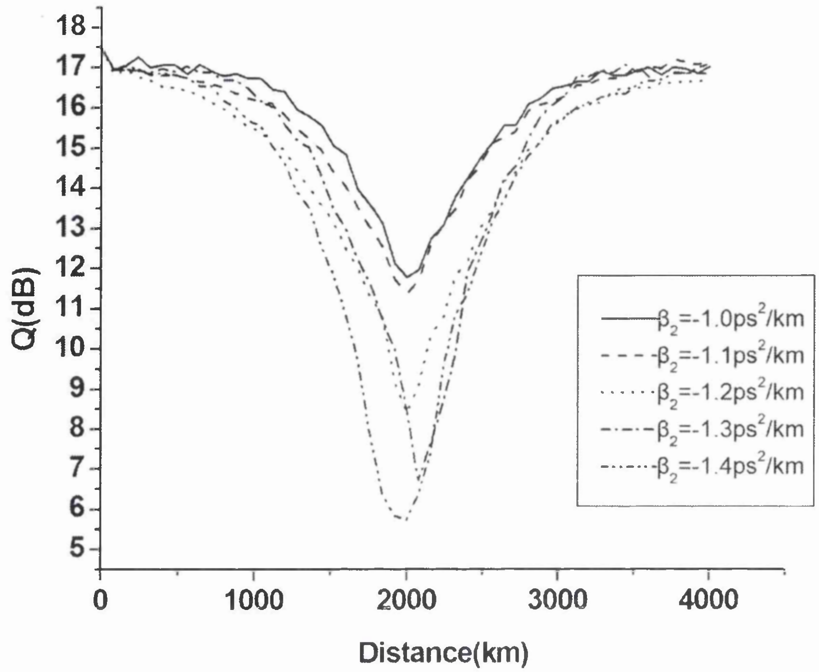


(g)

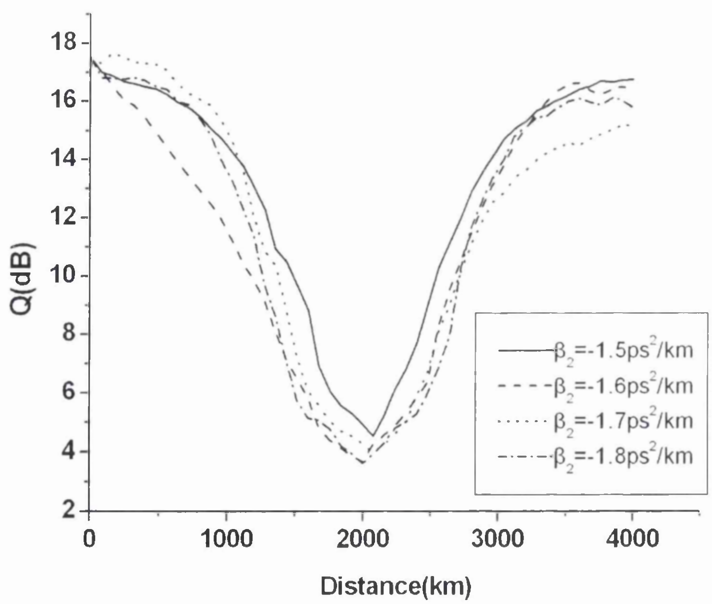


(h)

Figure 3.3 Eye patterns of central channel with different dispersion parameters in WDM systems (Raman amplifiers, soliton peak power). (a) is the eye pattern of β_2=-1.0ps^2/km at receiver. (b) is the eye pattern of β_2=-1.1ps^2/km at receiver. (c) is the eye pattern of β_2=-1.2ps^2/km at receiver. (d) is the eye pattern of β_2=-1.3ps^2/km at receiver. (e) is the eye pattern of β_2=-1.4ps^2/km at receiver. (f) is the eye pattern of β_2=-1.5ps^2/km at receiver. (g) is the eye pattern of β_2=-1.6ps^2/km at receiver. (h) is the eye pattern of β_2=-1.7ps^2/km at receiver.



(a)



(b)

Figure 3.4 The relationship of Q and distance for different dispersion parameters in WDM systems (Raman amplifier, soliton peak power). (a) is from $-1.0ps^2/km$ to $-1.4ps^2/km$. (b) is from $-1.5ps^2/km$ to $-1.8ps^2/km$.

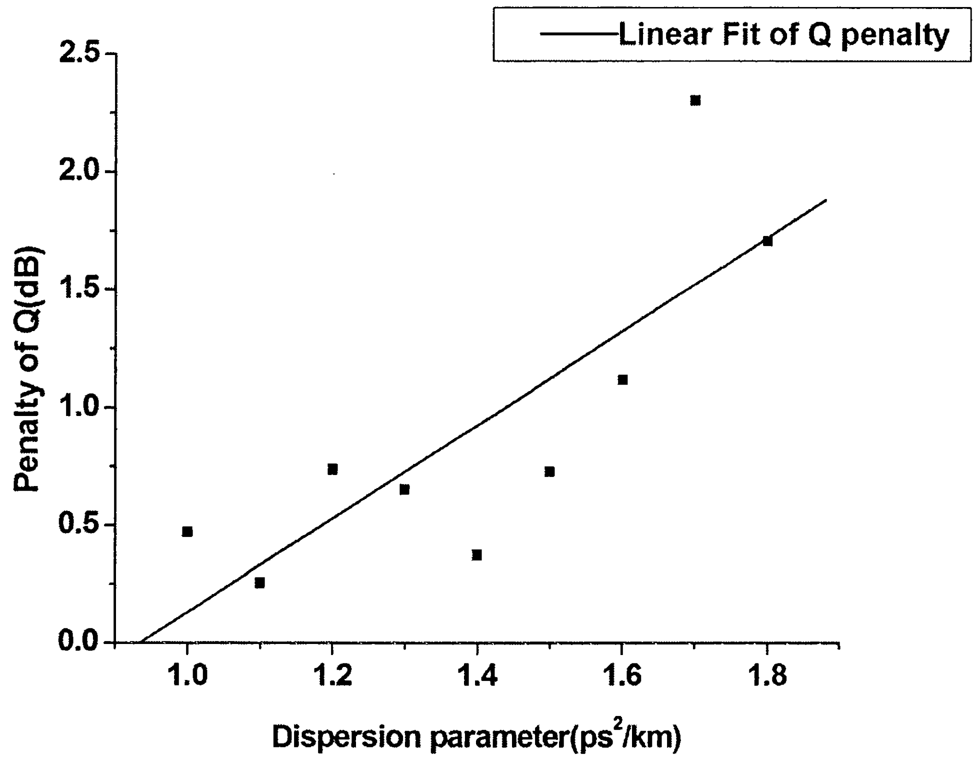


Figure 3.5 The penalty of Q value (dB) between receivers and transmitters relates to the dispersion parameters β_2 in Raman case.

By combining the results of Figure 3.3, we got the relationship of distance and Q value (See Figure 3.4). It is obvious that the curves could be partly recovered at the receivers and even if β_2=-1.8ps^2/km, the penalty of Q value is only 1.7dB. However, even though the general trend of penalty is that it increases slowly with the increase of dispersion [as shown in Figure 3.5], there is an exception at β_2=-1.7ps^2/km. The sharp increase of Q value's penalty is out of the trend. The reason of this is still unclear. It has to be declared that the Q value in Figure 3.3 is calculated by the eye diagram but the Q value in Figure 3.4 is calculated by the data from the output of this model. They are not numerically equal to each other.

One thing we noticed that the Q values calculated by code are not as big as we expected (over 20dB). However, the Q values shown in Figure 3.3, which is calculated by the eye diagram, are bigger than it in Figure 3.4. That means the problem is not relevant to the system. The issue could be the improper filter we selected to calculate the Q. In the code, the bandwidth of optical filter is 0.025THz and the cutoff frequency of the electrical filter is 0.006THz. However, in the NLSViewer, the bandwidth of optical filter is 0.025THz and the cutoff frequency of the electrical filter is 0.007THz. This issue will not affect the result since what we care is the penalty of Q value. Therefore, in this thesis this filter can be used but the appropriate filter would improve the results.

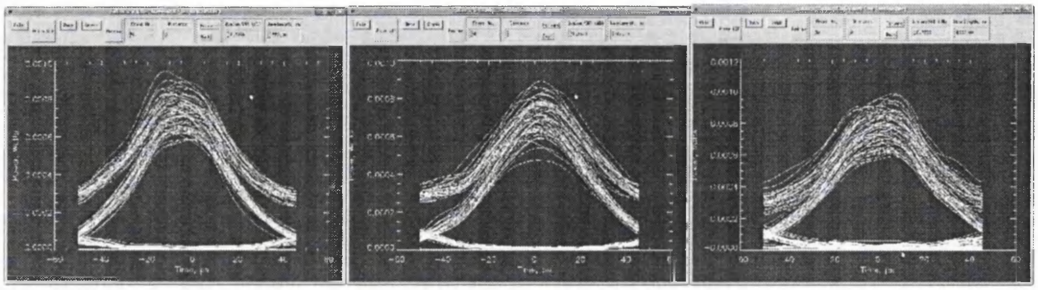
3.2 System performance with MSSI in WDM systems: EDFA

To be compared with, this section will provide the eye patterns and Q values in the same situation with Section 3.1 for the EDFA case. This link will have 6 channels (channel spacing is 50GHz), each channel includes 50 spans. Each span is 80 kilometers and the fiber loss is 0.2dB/km. There are Erbium-doped optical fiber amplifiers after every span. The gains of these EDFAs are 16dB to compensate the loss and the amplifier noise is not included. The transmission rate is 10Gbit/s, in another word, the bit period is 100ps. The single pulse is transformed into a 128-bitpattern and the pseudo random bit sequence (PRBS) size is 7.

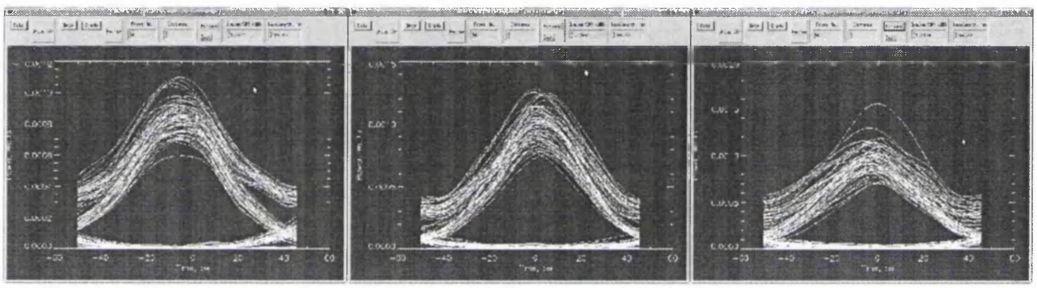
Figure 3.6 shows the eye patterns of fourth channel with different dispersion parameters in WDM systems. It is obvious that the eye opening height became lower and there is more noise due to dispersion and nonlinear effects when β_2=-1.5ps^2/km. That means MSSI cannot work as well as it did in Raman case which has this phenomenon when β_2=-1.6ps^2/km.

Figure 3.7 shows the relationship of Q and distance for different dispersion parameters in EDFA amplified WDM systems. Figure 3.8 shows the penalty of Q values at different dispersion. Based on these data, the general trend is that the penalty of Q value increases when the dispersion increases (as shown in Figure 3.8). Quantitatively, when the dispersion is bigger than 1.4ps^2/km (the penalty=2.7dB), the penalty of Q value will be over 3dB, which means the signal at the receiver will not be reliable. It has to be declared that the Q value in Figure 3.6 is calculated by the eye diagram but the Q value in Figure 3.7 is calculated by the data from the output of this model. They are not numerically equal to each other.

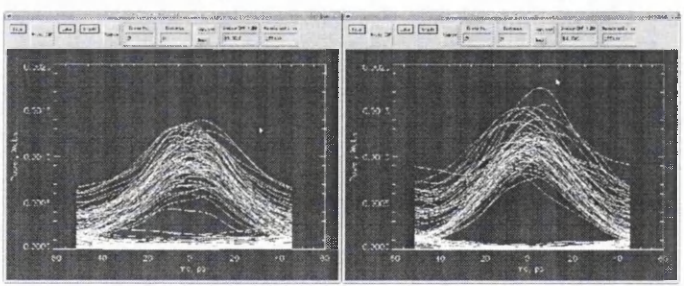
There is one more thing need to be noticed. When the dispersion parameter β_2 is equal to $-1.2ps^2/km$ and $-1.6ps^2/km$, the Q values reached the peak at about 3,000 kilometers and then went down again.



(a) (b) (c)

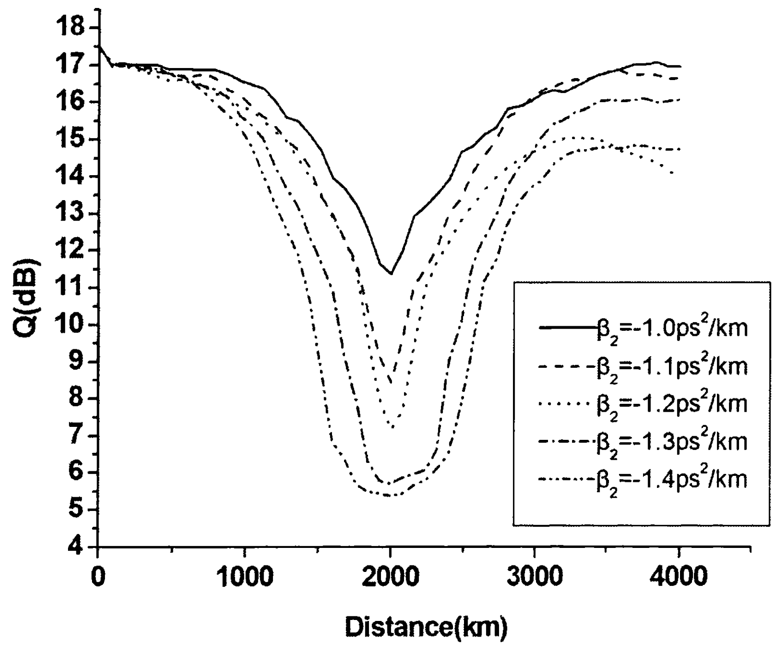


(d) (e) (f)

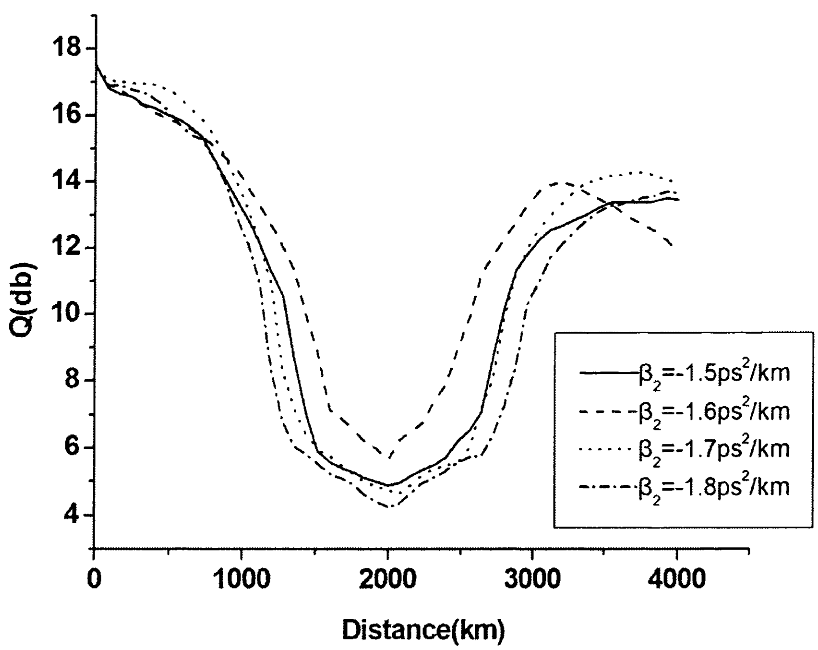


(g) (h)

Figure 3.6 Eye patterns of central channel with different dispersion parameters in WDM systems (EDFAs, soliton peak power). (a) is the eye pattern of $\beta_2=-1.0ps^2/km$ at receiver. (b) is the eye pattern of $\beta_2=-1.1ps^2/km$ at receiver. (c) is the eye pattern of $\beta_2=-1.2ps^2/km$ at receiver. (d) is the eye pattern of $\beta_2=-1.3ps^2/km$ at receiver. (e) is the eye pattern of $\beta_2=-1.4ps^2/km$ at receiver. (f) is the eye pattern of $\beta_2=-1.5ps^2/km$ at receiver. (g) is the eye pattern of $\beta_2=-1.6ps^2/km$ at receiver. (h) is the eye pattern of $\beta_2=-1.7ps^2/km$ at receiver.



(a)



(b)

Figure 3.7 The relationship of Q and distance for different dispersion parameters in WDM systems (EDFA, soliton peak power). (a) is from -1.0ps^2/km to -1.4ps^2/km. (b) is from -1.5ps^2/km to -1.8ps^2/km.

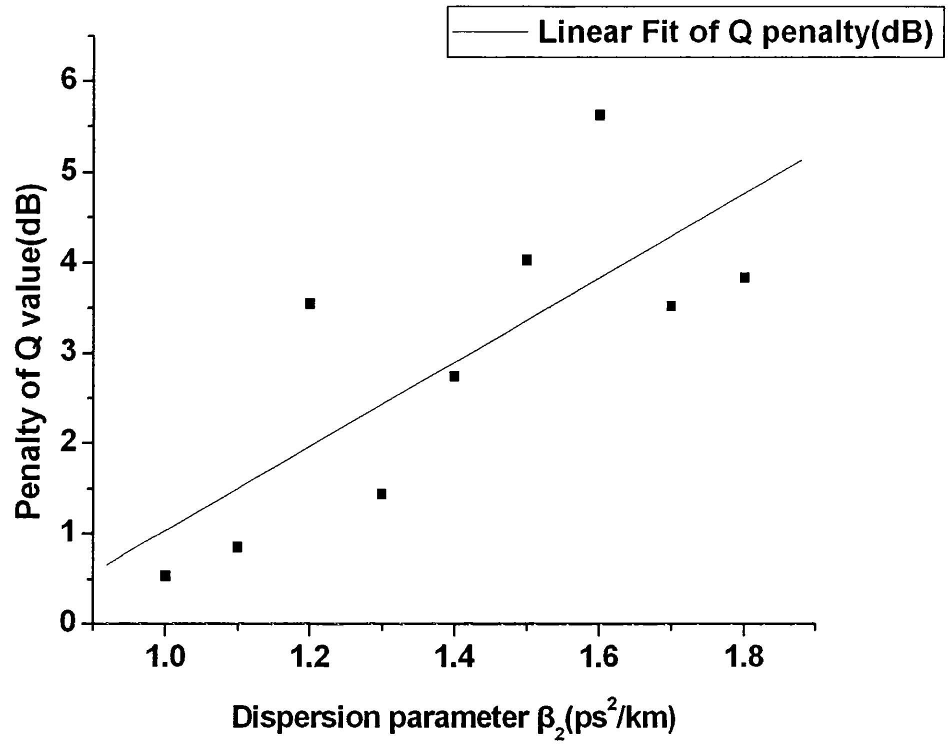


Figure 3.8 The penalty of Q value (dB) between receivers and transmitters relates to the dispersion parameters in EDFA case.

Obviously, mid-span spectral inversion could recover the signal at the receivers for both Raman amplifiers and EDFAs. However, MSSI is much more effective for Raman amplifier than EDFA. The reason is that Raman amplifiers are distributed amplifiers in the whole transmission link, which make the symmetry much better than EDFAs (see Figure 2.4). In EDFA case, the lack of symmetry affects the system performance with MSSI in WDM systems.

In next section, we are going to try to compare Raman amplifier and EDFA. It will be helpful to evaluate the difference between Raman amplifiers and EDFAs numerically.

3.3 Comparison of Raman amplifier and EDFA

As we found in section 3.1 and section 3.2, the difference of Q value between Raman amplifiers and EDFAs at the receiver is not big when the dispersion is not bigger than -1.2ps^2/km. Therefore, in section 3.3, only the Q value of Raman amplifiers and EDFAs of β_2=-1.0ps^2/km and β_2=-1.1ps^2/km will be numerically compared. Moreover, because the data when β_2 =-1.2ps^2/km is very strange, the Q value will also be compared. When it is bigger than this value, the difference between these two is large enough so it is not necessary to be evaluated numerically.

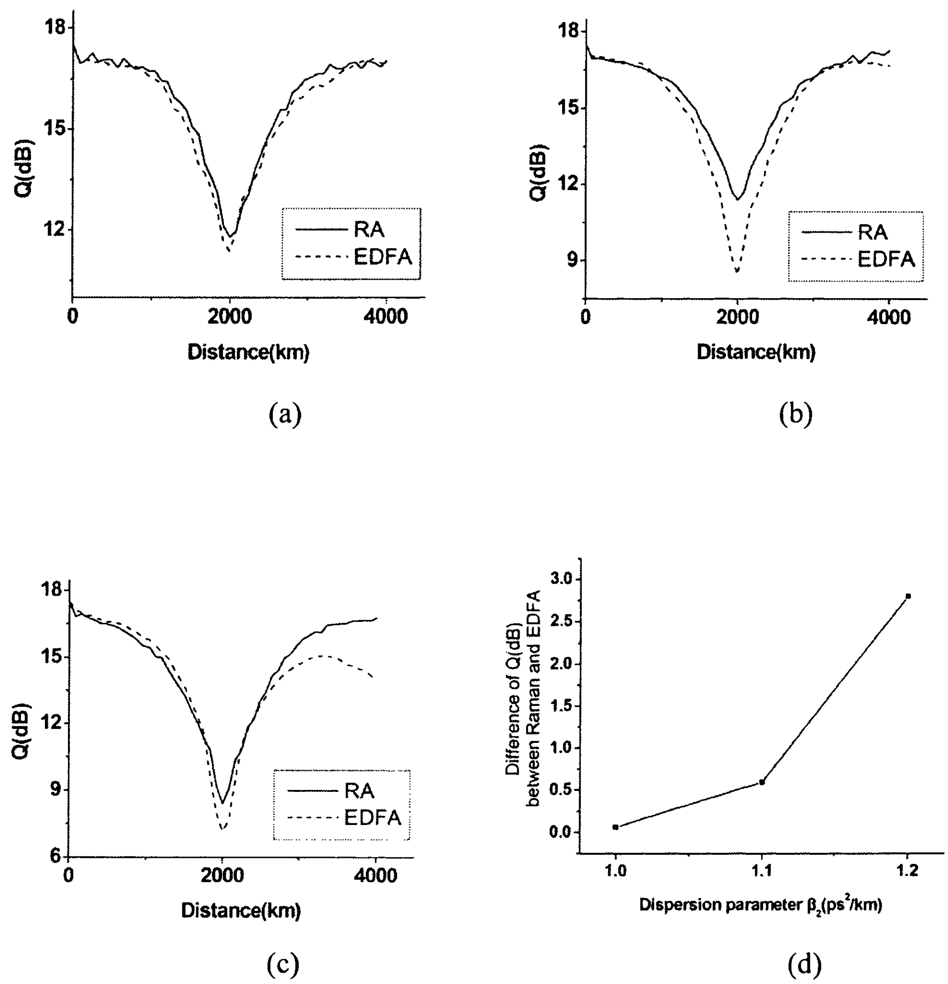
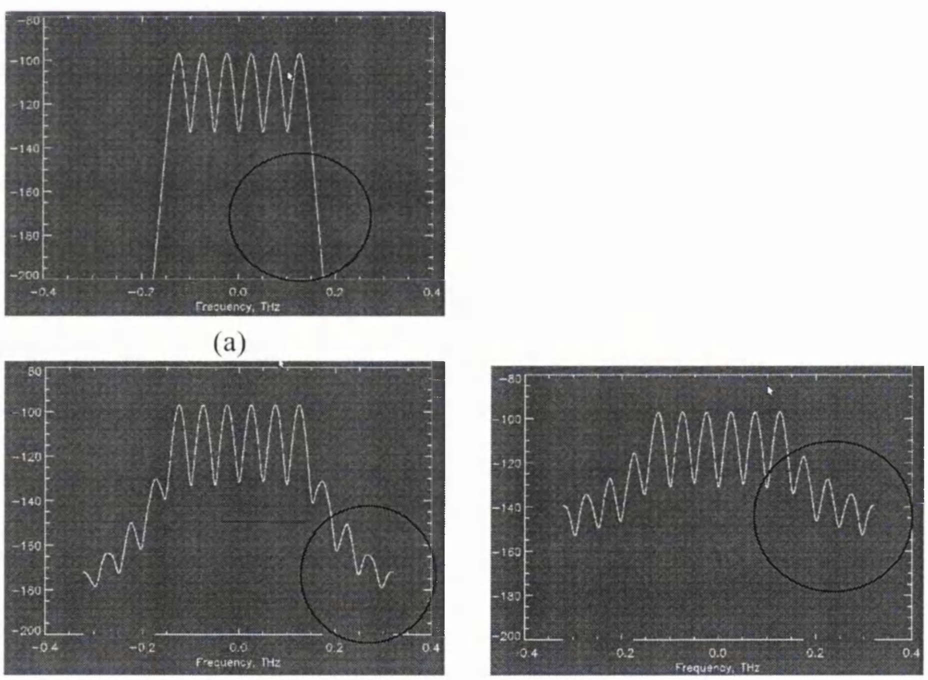


Figure 3.9 Comparison of Raman amplifier and EDFA of different dispersion parameters in WDM systems. (a) β_2=-1.0ps^2/km, the Q value at the receiver of Raman amplifier is 0.06dB bigger than EDFA. (b) β_2=- 1.1ps^2/km, the Q value at the receiver of Raman amplifier is 0.59dB bigger than EDFA. (c) β_2=-1.2ps^2/km, the Q value at the receiver of Raman amplifier is 2.81dB bigger than EDFA. (d) The difference of Q value between Raman amplifiers and EDFAs at receiver of β_2=-1.0ps^2/km, β_2=- 1.1ps^2/km and β_2=- 1.2ps^2/km.

As Figure 3.9 shows, even though the differences between Raman amplifiers and EDFAs in β_2=-1.0ps^2/km and β_2=-1.1ps^2/km are very small, Raman amplifiers are always have a bigger Q value than EDFAs. Figure 3.9(d) indicates that the difference of Q value between Raman amplifiers and EDFAs increases when dispersion increases for these several data. Then we should confirm whether this is the general trend between them.

To confirm these results, we are going to compare the log spectrum of Raman case and EDFA case. This log spectrum is also printed by the software named NLSViewer I introduced above. As figure 3.10 shows, the spectrum at the receivers of Raman amplifier and EDFA are different. In the black area, Raman amplifier almost kept the shape of initial, only some fluctuations. However, in EDFA case, the shape changed a lot. Then we confirmed that Raman amplifiers perform better than EDFAs with MSSI in WDM system (low dispersion, low power).



(a)

(b) (c)

Figure 3.10 Log spectrum comparison of Raman amplifier and EDFA (β_2=-1.2ps^2/km). The horizontal axis is frequency in THz and the vertical axis is power in dB. (a) is the initial spectrum at the transmitter for both Raman and EDFA case. (b) is the spectrum at the receiver for Raman case. (c) is the spectrum at the receiver for EDFA case.

Figure 3.11 indicates the comparison of Q value's penalty between Raman amplifier and EDFA. It gives an intuitive show about the difference of system performance between Raman amplifier and EDFA. Both of them have increasing general trends of Q value's penalties when the dispersion is increasing, but the penalty in EDFA case is overall bigger than the penalty in Raman case. Moreover, as it shows, the slope of EDFA is bigger than Raman amplifier. Then we can make a conclusion: Raman amplifiers perform better than EDFAs with MSSI in WDM systems under small power (the peak power of launched soliton).

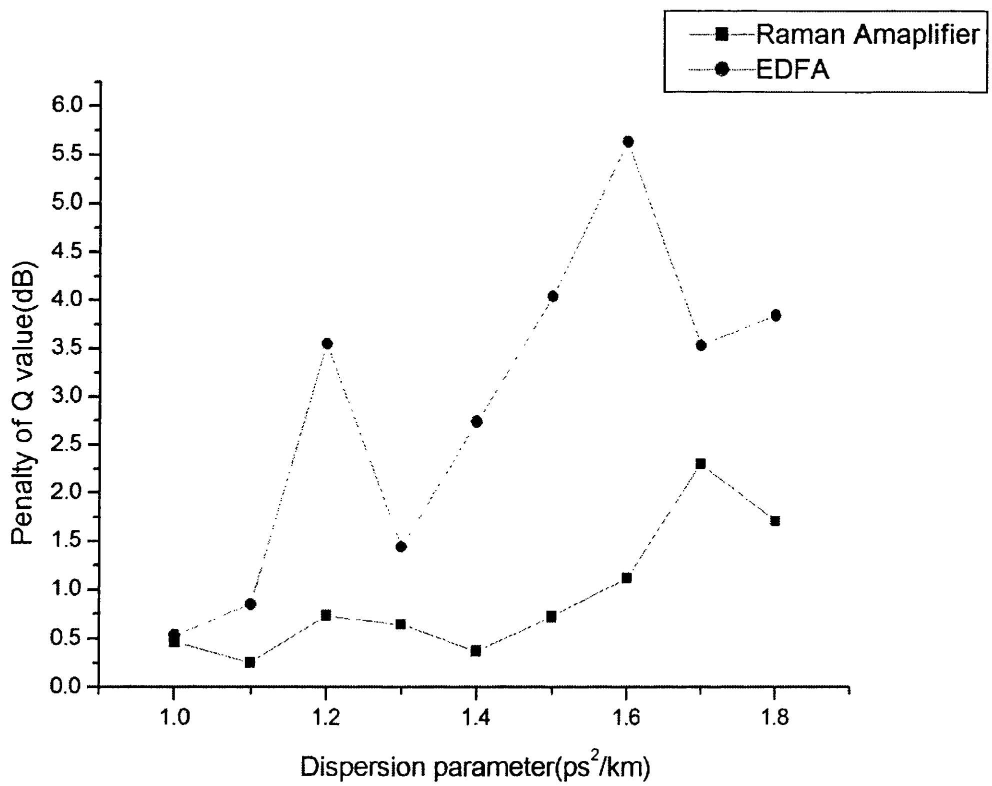


Figure 3.11 Comparison of Q value's penalty between Raman amplifier and EDFA (The dispersion parameters β_2 are from $-1.0ps^2/km$ to $-1.8ps^2/km$).

3.4 Comparison of Raman amplifier and EDFA in Standard Power

All the previous work I did in this project is based on the case that the launched power is the soliton power (smaller than the standard power), which is defined as anomalous.soliton_power (50, 1) in the code (50ps FWHM and the 1st order soliton). In this section, the standard power, which is 1mW (0dBm) will be used instead of soliton power, in order to figure out the result in standard fiber. In this model there are 6 channels with 50GHz channel spacing. Each channel has 50 spans with 80 kilometers each. The fiber loss is set as 0.2dB/km and the gains of amplifiers are 16dB and no amplifier noise.

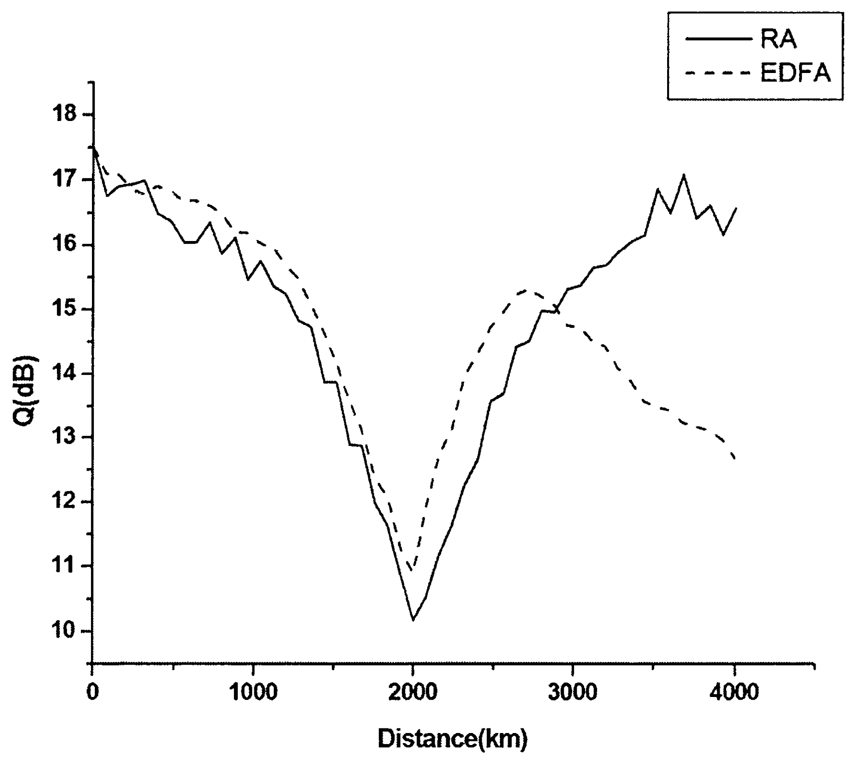


Figure 3.12 Comparison of Q values of Raman amplifiers and EDFA at the receiver in WDM systems with standard power. (Power=1mW, β_2=-1.2ps^2/km)

Based on the results in section 3.3, we know that the Q value at β_2=-1.2 ps^2/km is beyond the exception. Therefore we use this dispersion parameter as a sample to study the Q value in standard power. As shown in Figure 3.12, the Q value of Raman case is almost recovered at the receiver for low dispersion (β_2=-1.2 ps^2/km) in standard power (1mW) with mid-span spectral inversion (The penalty of Q value is about 1dB). However, for EDFA case, mid-span spectral inversion is not very effective (The penalty of Q value is more than 4.5dB), such as how it performed with the peak power of soliton in section 3.2 and section 3.3.

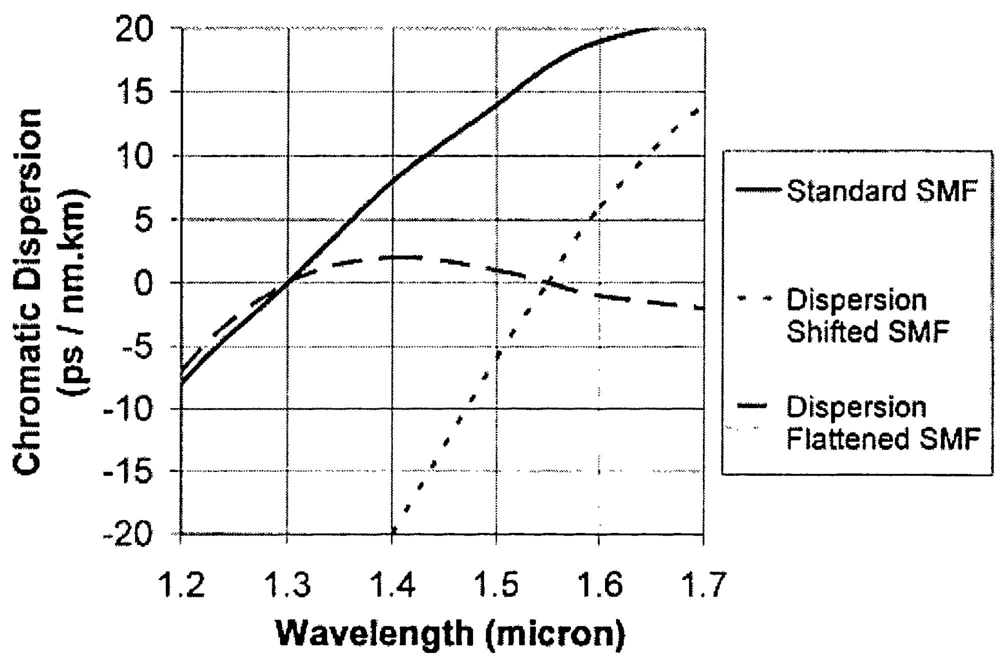


Figure 3.13 Dispersion characteristics of various fiber types. [after reference 10]

One thing we noticed that the curve of Q value for EDFA reached a peak at about 2,600 kilometers and went down again. Actually, referring to figure 3.13, we find that for standard single mode fiber, the ideal position of compensator will not be exactly at the mid-point of the link.[8] Based on this fact, we assume that moving the place where we set the optical phase conjugation may improve the performance for EDFA case. Figure 3.14 shows the comparison of different spans in which the optical phase conjugators (OPC) are set (β_2=-1.2ps^2/km, power=1mW). The mark which is pointed to by the red arrow is the original place where the OPC is set up in figure 3.14.Even though the trend shows periodically increases and decreases, the curve reaches the peak at the 31st and 32nd spans. Therefore figure 3.14 proves that if the optical phase conjugation is set at the 32nd span, the optimum Q value can be achieved for EDFA case.

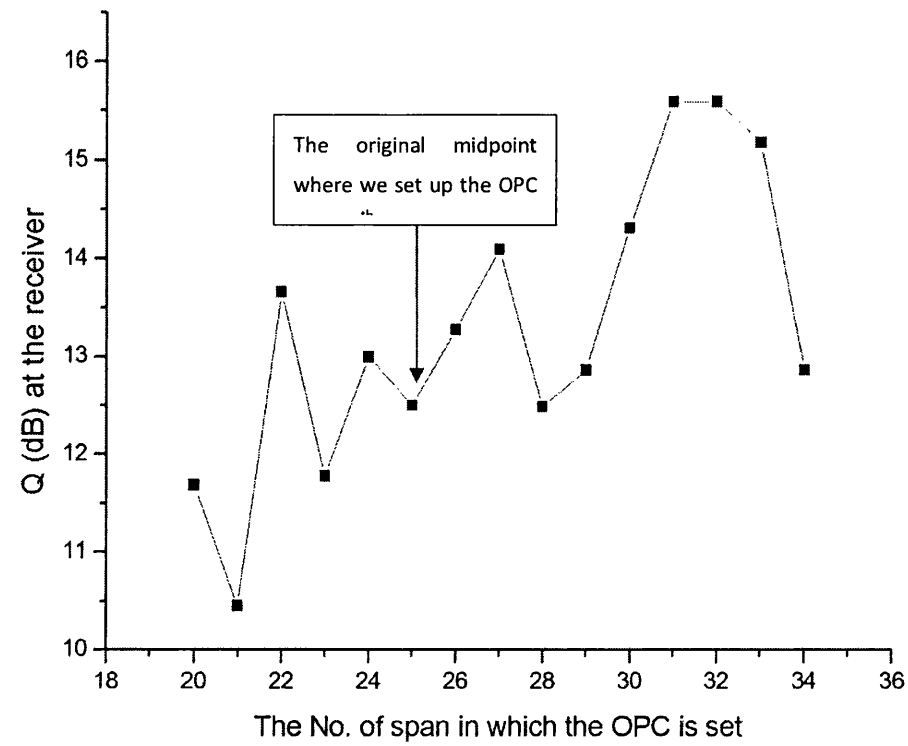


Figure 3.14 Comparison of Q (in dB) at the receivers by changing the place where the OPC is set. (EDFA, 1mW, β_2=-1.2 ps^2/km)

Based on the result shown in figure 3.14, we adjust the model and get the result of β_2=-1.2 ps^2/km (See Figure 3.15). The difference of Q value at the receiver between Raman amplifier and EDFAs is 0.98dB (the original difference is 3.90dB), which is a big improvement. However, as it is shown, even though we modified the conjugation point, the Q value for EDFA case is still 1dB lower than Raman case. That means Raman amplifiers perform better than EDFA in low dispersion situation with standard power.

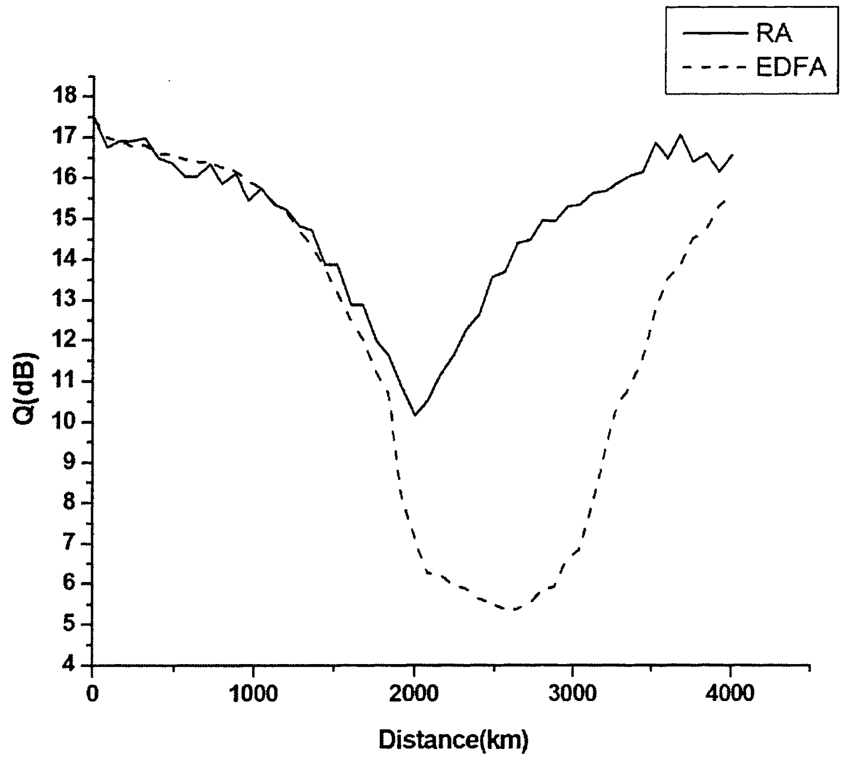


Figure 3.15 Comparison of Q values of Raman amplifiers and EDFAs at the receiver in WDM systems. Optical phase conjugator is set in the 32th span (2560km). β_2=-1.2 ps^2/km. Power=1mW.

3.5 Comparison of Raman amplifier and EDFA in Standard Fiber

In practical applications, the dispersion for standard fiber is about -20ps^2/km. Therefore, the results of standard dispersion (β_2=-20 ps^2/km) should be found out. Figure 3.16 shows the result we want to calculate. As shown, in Raman case, even though the Q value is very small (means the bit error rate is very large) at the mid span, it is almost recovered (about 15.6dB, 1.9dB lower than the initial Q) at the 4,000 kilometers, where is the distance we are going to set up the receiver. In EDFA case, the Q value is not perfectly recovered. Its initial Q is the same as Raman case and the Q at receiver is about 12.6dB, 4.9dB lower than the initial Q. Therefore, Raman amplification has 3dB benefit than EDFA with MSSI in WDM systems at standard situation (power=1mW and β_2=-20 ps^2/km)

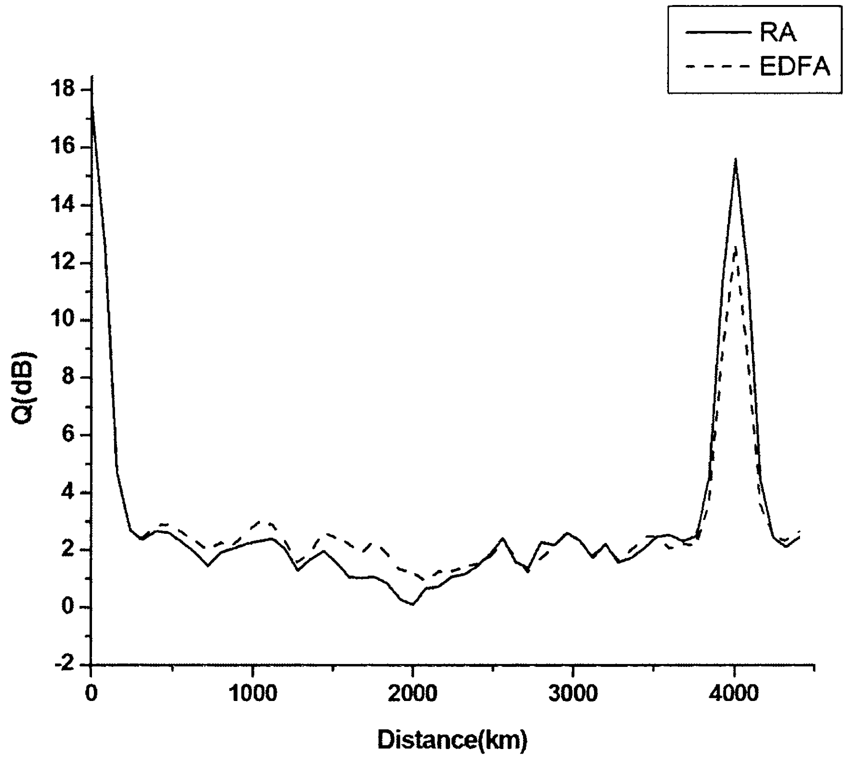


Figure3.16 Comparison of Q values of Raman amplifiers and EDFA at the receiver in WDM systems. (Power=1mW, β_2=-20 ps^2/km)

Considering that the optimum result is obtained by setting the optical phase conjugator at the 32nd span when β_2=-1.2 ps^2/km, it must be confirmed that whether the optimum result is obtained by setting the optical phase conjugator at the 25th span when β_2=-20 ps^2/km or not. Figure 3.17 proves that the optical phase conjugation is set at the 25th span to achieve the optimum Q value for EDFA case. Then the result in Figure 3.16 could be used as conclusion.

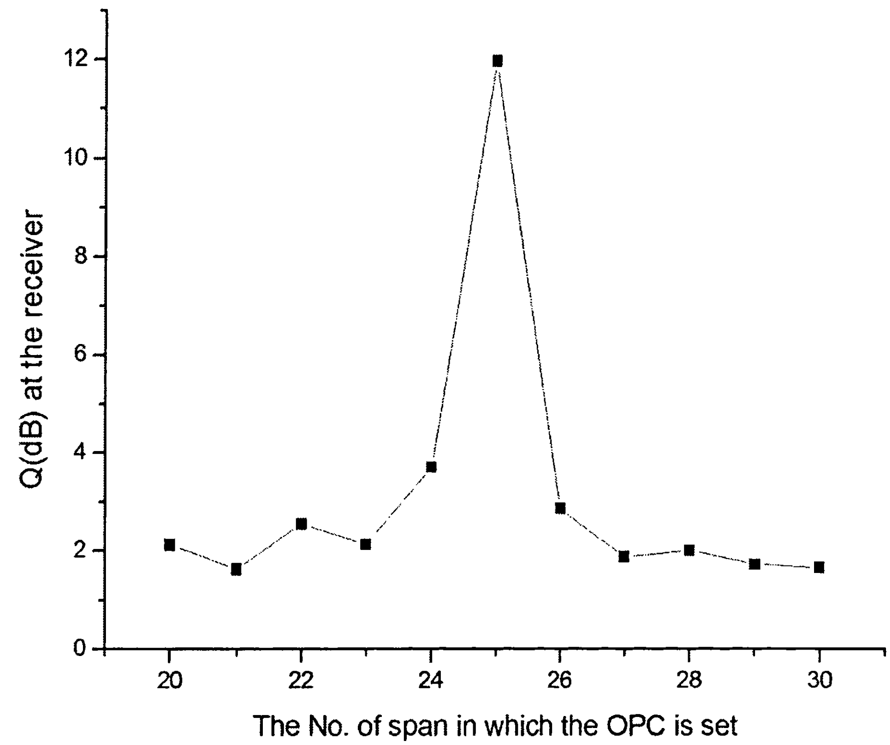


Figure 3.17 Comparison of Q (in dB) at the receivers by changing the place where the OPC is set (EDFA, β_2=-1.2 ps^2/km).

Based on above, it is obvious that in standard WDM systems (launched power is 1mW, dispersion parameter β_2=-20ps^2/km), Raman amplifiers are more suitable than EDFAs with mid-span spectral inversion technology. Furthermore, by combining Raman amplification and mid-span spectral inversion technology, the impairments caused by loss, group velocity dispersion and nonlinear effects could be compensated almost perfectly in this model. Then we came to the conclusion.

3.6 Summary

In this chapter, the model which is set up by the code gives a very good simulation even though several elements, such as amplifier noise and polarization are ignored. Firstly in section 3.1 to 3.3, we studied how MSSI WDM systems worked with Raman amplifiers and EDFAs in small power (the peak power of launched soliton) and small dispersion (less than $-2.0ps^2/km$) and conclude that MSSI WDM systems are conditionally effective for both Raman amplifiers and EDFAs. What is more, the results also prove that Raman amplifiers are more suitable than EDFAs in this case.

Then we increased the power to 1mW and studied the system performance again at $\beta_2=-1.2ps^2/km$. At the beginning we set up the OPC at the midpoint for both Raman amplifiers and EDFAs. The result was very good in Raman case, but the Q value cannot be recovered at the receiver in EDFA case. Then we modified the model by setting the midpoint at 32^{nd} and got the optimum Q value at the receiver. However the Q value of Raman amplifier still had 1dB benefit than this optimum Q value of EDFA.

In the end, we use $\beta_2=-20ps^2/km$, which is the standard dispersion in optical fiber transmission systems, instead of small dispersion. The result of this simulation in this case shows that even though the Q values are very small at the midpoint, they are recovered at the receivers in varying degrees for both Raman amplifiers (1.9dB penalty) and EDFAs (4.9dB penalty). Moreover, Raman amplifiers had 3dB benefit than EDFAs. That is the conclusion we want to make in this thesis.

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4. Conclusion and Future Work

In this thesis, a simple model of long distance transmission is established to prove that mid-span spectral inversion is theoretically effective for compensate the impairment caused by group velocity dispersion and nonlinear effects. The results of this project indicate that in both low dispersion (β is less than -2.0ps^2/km) low power (soliton peak power) situation and standard situation (launched power= 1mW, dispersion parameter β=-20ps^2/km), mid-span spectral inversion almost recovers the impairment during signal transmission. Actually, if Raman amplification is applied in this model, the difference of Q value (in dB) at the receiver and the Q value (in dB) at the transmitter could be ignored.

Another conclusion of this thesis is that Raman amplifiers are more effective than EDFA in this model. Previously in Chapter 2 it has been explained that distributed amplification of Raman amplifiers is more effective than EDFA to deal with the lack of symmetry in power caused by loss. And in Chapter 3, the result shows that in both low dispersion (β is less than -2.0ps^2/km) low power (soliton peak power) situation and standard situation (launched power= 1mW, dispersion parameter β=-20ps^2/km), the difference of Q value (in dB) of Raman case and EDFA case is about 3 dB at the receivers (See Figure 3.16). It practically proves that in WDM systems, Raman amplifiers are the amplifiers we need to compensate the impairment caused by loss with mid-span spectral inversion technology.

However, this model is simply established to study the impairment and compensation of loss, group velocity dispersion and nonlinear effects. The result is an approximation since some elements are not included. Therefore there are a lot we can do in the future work.

First of all, polarization is not included in this model which will affect the symmetry. Polarization could affect the results if it is included. In this thesis, the model is simplified by removing polarization because the main purpose of this research is to find out how MSSI works on fiber loss, group velocity dispersion and nonlinear effects. If this project can be processed further, polarization should be included to find out the effects. But I have no time to do this research in my project. It should be a great idea to do this in PhD program.

Second, in this model, noise is not considered to simplify the calculation. There is no doubt that noise will affect the results. However, the purpose of this thesis is to study how mid-span spectral inversion compensates impairment caused by loss, group velocity dispersion and nonlinear effects. So even though there is no noise in this model, it will not affect the conclusions.

Third, in this model, we used 6 channels instead of normal situation, for example, 80 channels. More channels may increase the cross talk between channels, but this part of impairment is not what we concerned.

The bit rate in this model is 10Gbit/s. If the bit rate increases, it may cause the change of calculation results. In the future work, more bit rates should be attempted, such as 40Gbit/s.

Furthermore, even though Raman amplification could reduce the lack of symmetry in power more effectively than EDFA, it is still not perfect (See Figure 2.2b). Therefore, the future works of this thesis are:

1. Consummate this model by including some other elements, such as noise. Then figure out the results and compare it with the results in this thesis.
2. Try to make the symmetry of power more perfect. One assumption is to increase the amplifier gain and use longer span as well. Another is increasing both the amplifier gain and fiber loss at the same time. These should be checked and then we can find out whether it works or not.

Appendix A: Pseudorandom bit sequence (PRBS)

A binary sequence (BS) is a sequence of N bits,

a_j for $j = 0,1,...,N - 1$,

i.e. m "1"s and N − m "0"s. A BS is pseudo-random (PRBS) if its autocorrelation function:

$$C(v) = \sum_{j=0}^{N-1} a_j a_{j+v}$$

has only two values:

$$C(v) = \begin{cases} m, & \text{if } v \equiv 0 \pmod{N} \\ mc, & \text{otherwise} \end{cases}$$

where

$$c = \frac{m-1}{N-1}$$

is called the duty cycle of the PRBS.

A PRBS is random in a sense since the value of an a_j element is independent of the values of any of the other elements, similar to real random sequences.

It is 'pseudo' because it is deterministic and after N elements it starts to repeat itself, unlike real random sequences. The PRBS is more general than the n-sequence, which is a special pseudo-random binary sequence of n bits generated as the output of a linear shift register. An n-sequence always has a 1/2 duty cycle and its number of elements $N = 2^k - 1$. PRBS's are widely used in telecommunication, encryption, simulation and correlation technique.

Appendix B: Main code for simulating MSSI in WDM systems (Raman amplifiers)

```
#include<gnls.h>
#include<string>
#include<iostream>
#include<iomanip>
using namespace std;

int main(){
 Amplifier::seed(0);
 int shiftN =7;
 int nperbit = 64;
 const double bit_period =100;
 const double optical_bandwidth=0.025;
 const double cut_off=0.006;
 int nbits =1 << shiftN;
 string output_name="soliton";
 Field field(nbits*nperbit/2,nbits*bit_period/2);
 Fiber anomalous(0,-2.0,0.0,0.0,1.55,0.2,50);
 OutputUnit out("soliton");
 QSeries Q_series;

 System system=
   Sech(50,2.29745*anomalous.soliton_power(50,1))+
    GeneratePattern(PRBS(shiftN,bit_period))+
    WDMify(-0.125,0.05,6)+
   OutputField(out)+
    25*(RamanAmplifiedSegment(anomalous,80,16,0)+Branch(QFactorCollect(Q_series,-
```

```
0.125,0.05,6,optical_bandwidth,cut_off,bit_period,nbits/2)+ OutputField(ou
t)))+Conjugate()+25*(RamanAmplifiedSegment(anomalous,80,16,0)+Branch(QFactorCollect(Q
_series,-0.125,0.05,6,optical_bandwidth,cut_off,bit_period,nbits/2)+Outp
utField(out)));
  system.propagate(field);

  ofstream Q_file((output_name+".Q").c_str());
  Q_file<<Q_series;

cout<<"uncompensated:z(10):"<<Q_series.Q_distance(10)<<"z(6):"<<Q_series.Q_distance(6)<<
endl;
  return 0;
}
```

Appendix C: Main code for simulating MSSI in WDM systems (EDFAs)

```
#include<gnls.h>
#include<string>
#include<iostream>
#include<iomanip>
using namespace std;

int main(){
 Amplifier::seed(0);
 int shiftN =7;
 int nperbit = 64;
 const double bit_period =100;
 const double optical_bandwidth=0.025;
 const double cut_off=0.006;
 int nbits =1 << shiftN;
 string output_name="EDFA";
 Field field(nbits*nperbit/2,nbits*bit_period/2);
 Fiber anomalous(0,-1.0,0.0,0.0,1.55,0.2,50);
 OutputUnit out("EDFA");
 QSeries Q_series;

 System system=
   Sech(50,2.29745*anomalous.soliton_power(50,1))+
    WDMify(-0.125,0.05,6)+
    GeneratePattern(PRBS(shiftN,bit_period))+
   OutputField(out)+
    25*(FiberSegment(anomalous,80)+Amplifier(16,0)+Branch(QFactorCollect(Q_series,-
```

```
0.125,0.05,6,optical_bandwidth,cut_off,bit_period,nbits/2)+ OutputField(
out)))+Conjugate()+25*(FiberSegment(anomalous,80)+Amplifier(16,0)+Branch(QFactorCollect(
Q_series,-0.125,0.05,6,optical_bandwidth,cut_off,bit_period,nbits/2)+
OutputField(out)));
  system.propagate(field);


  ofstream Q_file((output_name+".Q").c_str());
  Q_file<<Q_series;


cout<<"uncompensated:z(10):"<<Q_series.Q_distance(10)<<"z(6):"<<Q_series.Q_distance(6)<<
endl;
  return 0;
}
```